BELL TELEPHONE LABORATORIES
INCORPORATED

SUBJECT: Project Apollo - Study of Carrier Interruption Effects on Phase Locked Loop Operation - Case 20061

DATE: September 16, 1965

FROM: J. C. Lumsden

MF5-4334-18

ABSTRACT

There is a possibility that antenna pattern nulls and spacecraft maneuvers will cause the rf carriers of Apollo S-band telecommunication and tracking systems to be interrupted for varying time intervals. Since the receivers employ phase-locked oscillator (PLO) loops, all information will be lost for a time interval at least as great as the time that the carrier is actually interrupted. This memorandum considers the relation between carrier interruption effects and PLO loop characteristics of the PM systems. The FM system is not considered in this memorandum.

Doppler frequency shifts caused by varying spacecraft velocities will cause the voltage-controlled oscillator (VCO) of each tracking loop to be shifted from its normal oscillating frequency. If a Doppler-frequency-shifted input signal is interrupted after a phase-locked oscillator (PLO) loop has been locked to the phase of the input signal, the loop will become unlocked and the VCO will tend to return to its undisturbed frequency of oscillation at an exponential rate (return drift rate) determined by the time constant of the loop filter. The PLO loop will automatically begin to pull into lock with the input signal when the signal is again received, provided that the signal is within the bandwidth of any narrow bandpass filter prior to the detector. The time required for the loop to pull into lock is proportional to the square of the frequency difference between the PLO loop and the input signal and inversely proportional to the cube of the loop noise bandwidth.

Equations and curves are included for determining PLO return drift rate, pull-in time, Doppler shift, allowable carrier interruption time that will permit the tracking loop to reacquire the carrier after an interruption or to pull in to lock with a subcarrier, and for determining the total information outage time.

The up-carrier tracking and demodulating loops will automatically reacquire their signals for up-carrier interruptions of less than about 0.2 seconds during maximum Doppler conditions experienced in the earth parking orbit or for interruptions of less than about 0.1 seconds during translunar injections. The interruption time for the down carrier will be slightly less for automatic reacquisition. Thus, short carrier interruptions can require manual or programed reacquisition while the spacecraft is in the near earth trajectories.

[redacted]

DISTRIBUTION

Messrs. J. J. Hibbert - Bellcomm
C. R. Moster - Bellcomm (50)
C. A. Armstrong - WH
R. P. Booth - WH
R. Cerino - WH
P. V. Dimock - WH
E. Goldstein - WH
R. J. McCune - WH
G. H. Myers - WH
R. C. Peterson - WH
C. W. Schramm - WH
H. R. Westerman - WH
M. P. Wilson - WH
R. O. Wise - WH

TABLE OF CONTENTS

BELL TELEPHONE LABORATORIES
INCORPORATED

SUBJECT: Project Apollo - Study of Carrier Interruption Effects on Phase-locked Loop Operation -

DATE: September 16, 1965

FROM: J. C. Lumsden

MF5-4334-18

MEMORANDUM FOR FILE

INTRODUCTION

The Apollo Unified S-band Telecommunication and Tracking System employs phase-locked oscillator (PLO) techniques for phase tracking the PM carrier and for demodulation of some of the communication subcarriers.[1] All phase-locked oscillators are initially locked-on to their respective signals by a standard acquisition procedure. After initial acquisition, there is a possibility that the up or down rf carrier or both will be interrupted for varying time intervals as a result of antenna pattern nulls and spacecraft maneuvers. This is particularly true while the spacecraft is in the near vicinity of the earth, i.e., less than 10,000 miles altitude, when the spacecraft signals are transcieved simultaneously over two omnidirectional antennas located on opposite sides of the Command Module's forward section. Phasing effects between the two antennas then will produce signal variations as the orientation of the space vehicle changes relative to a ground station. Momentary equipment failures could produce the same effects.

Any interruption or loss of carrier will cause all PLO loops in a voice or data channel to become unlocked. The voltage-controlled oscillators (VCOs) in the unlocked PLO loops will drift toward their undisturbed oscillating frequencies while the carrier is absent and will require a measurable time to pull back into phase lock after the carrier is again received. All information on the carrier will be lost until the PLOs have regained phase lock.

---

[1] All superscripts refer to a list of references at the end of the memorandum.

It is of interest to know quantitatively whether to expect interruptions of the S-band signal due to the spacecraft antenna pattern and maneuvers, and if so, how often and for how long when the interruptions occur. This memorandum considers the pull-in time required by a PLO tracking loop to lock onto the phase of an input carrier or subcarrier following a signal interruption. The factors that affect pull-in time - such as oscillator drift rate, narrow bandpass filter effects, loop noise bandwidth, and Doppler shift - are also discussed.

Since the unified S-band PM systems for the Apollo Command-Service Module (CSM) and the Lunar Excursion Module (LEM) are essentially the same, only the CSM and ground station systems are discussed.

PLO LOOPS

General

Figure 1 shows the block diagram of a standard PLO loop.[1,2,3] It includes a local reference VCO, a phase detector that compares the relative phase difference between the received signal and the oscillator, a loop filter which partly determines the transfer characteristic of the PLO loop, and a reactance modulator for controlling the oscillator frequency. The loop gain has the dimension of frequency and its magnitude is also the holding range of the PLO.

The Apollo system employs two types of tracking loops. One type (Figures 2, 2A) is the carrier tracking loop which employs a narrow bandpass filter prior to the detector that allows the spectral line of the carrier being tracked plus noise and intermodulation products that fall within the filter bandwidth to enter the innermost loop. This loop is termed modulation restrictive.

The second type is used to demodulate the angle-modulated subcarrier signals and is usually called a modulation tracking loop. The demodulating loop is similar to the basic carrier tracking loop; however, the loop filter has a bandwidth sufficient to accommodate the modulated signal. The output signal from a demodulation loop is taken at the output of the low-pass loop filter (Figure 3).

The carrier tracking loop in the main reference channel receiver of the Apollo ground station is similar to that of the CSM except that a stable reference signal is injected at two mixer stages. The VCO of the ground receiver can also be controlled for manual or programmed signal acquisition.

A block diagram and partial schematic of the carrier tracking loop for the CSM receiver will be used as a model PLO loop for various calculations made in this memorandum. The additional frequency multipliers, IF amplifiers and mixer stages of Figure 2 or 2A contribute only to the over-all gain of the linearized loops. The effect of the narrow bandpass crystal filter in the second IF of the tracking loop will be considered later. Weaver[4] has shown that the complex loop of Figure 2 or 2A is reduceable to the basic loop of Figure 1 and that the design or analysis of the complex loop is only slightly more difficult than the design or analysis of the basic PLO loop.

Pull-in and Tracking Range

The maximum pull-in range is the largest frequency difference from the VCO natural frequency for which pull-in can be obtained, regardless of the length of time required for the purpose. Practical designs avoid the requirement for pull-in from frequency deviations approaching the maximum because the pull-in time could then be infinitely large. The normal procedure is to specify a pull-in time that is satisfactory for operational purposes and then design the loop to satisfy the allotted pull-in time.

Once the PLO is locked onto the input signal above threshold, the PLO will remain locked until the input signal frequency shift is greater than the tracking range, or until the frequency shift rate exceeds the loop tracking capability. If either condition is violated, the PLO will lose lock.

The pull-in range is always less than the tracking (or holding) range if a narrow bandpass or loop filter is included in the PLO loop. Furthermore, the inclusion of a narrow bandpass filter in front of the limiter limits the pull-in range to one-half the filter bandwidth; this will be discussed again in a later section. The loop filter controls the PLO loop equivalent noise bandwidth and thus affects both the pull-in range and pull-in time.

Pull-in Time

Pull-in time is defined as the length of time required to gain phase lock between the PLO loop and the input carrier without manual or programmed assistance. The characteristics of the PLO loop which affect pull-in time are the equivalent noise bandwidth, the damping ratio, and the undamped natural frequency. These characteristics can be determined by an analysis of the loop or are chosen during loop design.

The pull-in time can be obtained for any specific frequency difference between the received carrier and the frequency output from the PLO loop by the phase plane plot technique,[5] which involves the solution of a nonlinear differential equation. However, the pull-in time (T_p) cannot be more than indicated by the following equation[6,10]

$$T_p = \left(\frac{\pi}{K^2}\,\frac{\delta f}{2}\right)^2 \left(\frac{K^2 + \frac{1}{4}}{B_\ell}\right)^3 \tag{1}$$

where

T_p = pull-in time in seconds

δf = frequency difference between the input signal and the PLO loop at the first mixer or phase detector, in cps

K = PLO loop damping ratio

B_ℓ = PLO loop equivalent one-sided noise bandwidth in cps

Equation (1) applies where the loop noise bandwidth remains relatively constant over the pull-in period. The formula also applies provided that there is no narrow bandwidth filter ahead of the phase detector, or in any event that the input difference frequency δf is within the passband of the filter. The effect of including such a filter, as shown in Figures 2 and 2A, will be considered later.

It has been found[1] that loop damping ratios between 0.5 and 1.0 give the best pull-in times. Viterbi[3] and Richman[6,10] both derive approximate values for the time required for a loop to pull into lock for some initial frequency offset, $\Delta\omega$, for high gain second order loops with K equal to $1/\sqrt{2}$.

An alternate term of the pull-in time equation is given by Viterbi[3] as:

$$T_p \cong \frac{(\Delta\omega)^2}{2K\,\omega_n^3} \text{ sec} \tag{2}$$

or in terms of loop noise bandwidth B_ℓ:

$$T_p \cong \frac{[2\pi(\delta f)]^2}{2K\left[\dfrac{2B_\ell}{K + \frac{1}{4K}}\right]^3} \text{ sec.} \tag{3}$$

The expression for B_ℓ, and for the damping ratio K, is derived in Appendix A. ω_n is not the natural frequency ω_o of the VCO itself; instead, it describes the rate at which the system would oscillate about the VCO frequency if the resistance in the loop was zero. ω_n also describes the optimum rate at which the VCO should be varied by an outside force if the VCO is to be swept through a frequency band to expedite signal acquisition by the PLO loop.

Limiter Effects

If a limiter precedes or is included in the loop, it inserts a variable loop gain figure corresponding to the limiter suppression factor, α. This variable loop gain causes the loop noise bandwidth to vary.[7] The loop noise bandwidth increases with the limiter suppression factor, and hence increases with the S/N power ratio at the limiter input. Thus, the tracking loop limiter provides an adaptive feature in phase-lock loop operation. For large S/N ratios in the loop, the loop noise bandwidth is large which provides a relatively fast carrier tracking response in the loop and for small S/N ratios, the loop noise bandwidth is decreased which reduces the carrier tracking error in the loop due to thermal noise. The Apollo CSM tracking loop noise bandwidth ($2B_{\ell}$) varies from about 700 cps at the threshold S/N ratio, to 2500 cps at S/N ratios greater than about 10 db.

The introduction of the limiter suppression factor[2,9] with its related effect on noise bandwidth complicates the expression for pull-in time given earlier. Appendix B shows that when the limiter is included, pull-in time for signals above threshold may be estimated by the following modification of the earlier equation (1):

$$T_p \approx \left[\frac{\pi(\delta f)}{2\left(K_{th}\sqrt{\frac{\alpha}{\alpha_{th}}}\right)^2} \right]^2 \left[\frac{K_{th}^2 + \frac{1}{4}}{B_{th}} \right]^3 \tag{4}$$

where

K_{th} = threshold loop damping factor

α_{th} = threshold limiter suppression factor

The value of α corresponding to a particular S/N ratio above threshold may be obtained from Figure 4. The α_{th} for the CSM (Block II) tracking loop threshold S/N is 0.188 for a $2B_{th}$ of 700 cps as stated above. The ground station may select any of three $2B_{th}$ bandwidths, presently specified as 50, 200, and 700 cps.

The B_{th} and B_{ℓ} one-sided noise bandwidths are related approximately by the following expression when the threshold design value for K is 0.707. This threshold K is used in designing the carrier tracking loops of Apollo.

$$B_{\ell} = \frac{B_{th}}{3}\left(2\,\frac{\alpha}{\alpha_{th}} + 1\right) \tag{5}$$

The $2B_{th}$ and α_{th}^{11} factors for the CSM (block II) and ground station loops are summarized in the following table.

System	$2B_{th}$ in cps	α_{th}
CSM	700	0.188
GS1	50	0.071
GS2	200	0.141
GS3	700	0.282

Pull-in time based on equation 4 and the above table (CSM and GS-3) for signal-to-noise ratios in the actual tracking loop bandwidth of 6 and 12 db are plotted in figures 5 and 6 for a δf extending slightly beyond the limits of the bandpass limiter.

PLO Loop Return Drift Rate

After the carrier tracking loop has been locked-on to an incoming carrier, the PLO loop frequency generally will be shifted from its undisturbed frequency of oscillation, f_o. If the carrier then is interrupted, the carrier tracking loop (and all succeeding loops) will become unlocked and the oscillator of each loop will tend to return to the undisturbed VCO frequency at a rate determined primarily by the time constant of the low-pass loop filter of each loop.

The return drift rate is developed here in terms of the up-carrier tracking loop for the CSM receiver (Figure 2). If the incoming signal to the CSM is lost, the circuit is reduced to the components shown inside the dashed lines of Figure 2. If the gain constant for the frequency divider (x 1/2) is included with the oscillator, then Figure 2 reduces to the basic PLO configuration (Figure 1). The partial circuit schematic is shown in Figure 7. With the carrier missing, only the VCO/2 signal and band-limited noise are present at the phase detector. The control voltage output of the detector with no carrier input other than band-limited noise can be assumed to be zero on the average.

For frequencies within the pass band of the low-pass loop filter, the high impedance values of the picofarad capacitors and varactor diodes allow the circuit of Figure 7 to be reduced to that of Figure 8. While the loop is tracking the carrier, C-13 in the low-pass filter is sufficiently charged to unbalance the reactance modulator (varactor diode CR2 and CR4 of Figure 7) to compensate for the frequency shift required to maintain phase lock. When the carrier is lost, C-13 begins to discharge at a rate determined by the time constant T_1 = RC of Figure 8. Since most of the resistors are small in value when compared with R1 plus R2 of this circuit, Figure 8 can be further simplified as shown in Figure 9. The exponential discharge rate of C-13 reduces the reactance modulator control voltage $\rho_r(\tau)$ to

$$\rho_r(\tau) \cong E_o e^{-\frac{\tau}{RC}} \cong E_o e^{-\frac{\tau}{T_1}} \qquad (6)$$

where E_o is the voltage measured across C-13 at the time of signal interruption and τ is time measured from the instant of signal interruption. As the modulator control voltage decreases toward zero, the loop frequency tends to return to its undisturbed oscillating frequency f_o. If the carrier is absent for one time constant (τ/RC = 1), the loop will have returned to a frequency $f_o \pm 0.37$ Df, where Df is the difference between f_o and the incoming carrier frequency that reflects the Doppler shift experienced at the time of the carrier interruption (see Figure 10). Other system instabilities that could cause frequency shift are neglected here. If the carrier is received again at the end of one time constant, there will be a frequency error δf between the carrier and PLO loop frequencies of 0.63 Df cps. Similarly, if the carrier is absent for two time constants, the frequency error will equal 0.87 Df, and after four time constants it will equal 0.98 Df. The general equation for determining δf is

$$\delta f \cong Df\left(1 - e^{-\frac{\tau}{T_1}}\right) \quad (7)$$

Bandpass Filter Effect on Loop Pull-in Capability

Special consideration must be given to pull-in times and acquisition procedures when a narrow bandpass filter is included in front of the PLO loop detector as shown in Figures 2 and 2A. The PLO loop will begin automatically to pull into lock with the carrier, either for initial acquisition or after a carrier interruption, provided the carrier frequency falls within the pass band of the filter. However, if the bandwidth of the filter is BW, then any difference δf between the input carrier frequency and the loop frequency at the first mixer that is greater than BW/2 will prevent the loop from automatically pulling into phase lock. In the latter case, only band-limited noise will be presented to the phase detector, and the VCO either will remain at its undisturbed frequency of oscillation f_o or, following a carrier interruption, will return to f_o at the rate cited in the previous paragraph.

Depending on the amount that the carrier is shifted from the loop natural frequency after phase lock has been established, a narrow bandpass filter preceding the PLO loop detector may limit the time that the carrier can be interrupted and still have the loop automatically pull back into lock when the carrier is restored. This factor can be particularly significant if there is a sizable Doppler shift of the carrier frequency, as will be brought out further in the following section.

DOPPLER FREQUENCY SHIFT EFFECT ON APOLLO SYSTEM CARRIER ACQUISITION

The amount of loop phase shift or frequency shift required in order to lock-on to an input carrier is determined by the Doppler shift resulting from the relative radial velocity between the CSM and the ground station, and by inherent oscillator drift characteristics. The relative magnitudes of these two factors will vary widely, and either may be predominant at a given time. For example, when the CSM first appears over the horizon of a ground station during the Earth parking orbit, relative radial velocity will be high, and the Doppler shift will be correspondingly high and will probably exceed the oscillator drift; as the CSM passes directly overhead, the Doppler shift will reduce gradually to zero, and for some interval of time probably will be less than the oscillator drift.

In general, it can be assumed that the short-term stability of the CSM oscillator, and certainly of the ground station oscillator, will be good enough that any drift during carrier interruptions of seconds or a few minutes duration will be negligible compared to the maximum Doppler shift that can be encountered. On this assumption, further attention here is restricted to the effects of Doppler shift.

Given an up-carrier frequency of f_1 (=2.1064 gc) the received signal (f_2) at the CSM is changed by the Doppler shift to

$$f_2 = f_1 \left(1 \pm \frac{V}{C}\right) \tag{8}$$

where

V = radial velocity of the CSM relative to the ground station

C = propagating velocity of light

The transmitted signal from the CSM (f_3) is phase-locked to the VCO of the receiver for ranging purposes, and is equal to f_2 multiplied by 240/221 to provide carrier separation. The transmitted signal from the CSM is then

$$f_3 = f_1 \left(1 \pm \frac{V}{C}\right) (240/221) \tag{9}$$

The received signal at the ground station is then

$$f_4 = f_3\left(1 \pm \frac{V}{C}\right) = (240/221)\ f_1\left(1 \pm \frac{V}{C}\right)^2 \qquad (10)$$

Thus, the down-carrier is affected by a two-way Doppler.

The relative radial velocity between the CSM and a ground station varies from zero at launch to about 36,400 ft/sec at translunar injection and then decreases to less than 2000 ft/sec at the gravitational equilibrium point between the earth and the moon. The relative velocity can vary from zero to about ±10,000 ft/sec while the CSM and LEM are in the lunar parking orbit.

The Doppler frequency shift, Df, resulting from any radial velocity encountered during the mission is shown in Figure 11. These curves are based on an f_1 of 2.1064 gc. The maximum Df would be encountered while the CSM is in a near-earth trajectory, more specifically, at translunar injection. At that time, the Doppler shift of the up carrier could be almost ±80 kc. Thus, the bandpass filter ahead of the PLO loop detector in the CSM would require a bandwidth of about 160 kc to allow the loop to automatically pull into phase lock with the carrier either initially or following a carrier interruption of any length. If such a wide filter were available in the circuit, Figures 4 and 5 could be used to determine the pull-in time required to gain phase lock. However, since the bandpass filter actually designed for the CSM carrier tracking loop has a bandwidth considerably less than twice the maximum expected one-way Doppler shift, manual or programmed assistance generally must be available to lock or relock the loop. The same is true, of course, for the ground station receiver since it includes an even narrower bandpass filter.

APOLLO SYSTEM ACQUISITION PROCEDURES

Initial Acquisition

Information on acquisition procedures and equipment for implementing signal acquisition is not complete; however, the presently discussed acquisition plan calls for a programmed procedure initiated by an operator at a tracking station. The operator at a tracking station will push a button to initiate the acquisition program that will off-set the tracking station transmitter frequency by a predicted minus Doppler and the tracking station receiver by a plus Doppler when the range between the spacecraft and the station is decreasing. If the range is increasing, the operator will push a second button that will cause the transmitter frequency to be shifted by a plus Doppler and the receiver to be shifted by a minus Doppler. (Whether this frequency shift is the actual Doppler experienced at the time of acquisition or the maximum possible Doppler is presently uncertain.) The acquisition program will then cause the tracking station transmitter to sweep through ±90 kc about the off-set frequency at a rate of 35 kc per second. After both up and down carriers have been acquired by the carrier tracking loops and the modulated subcarriers have been added to the carrier, the program will stop the transmitter from sweeping and will return the transmitter to its undisturbed transmitting frequency at a slow rate that will allow the tracking loops to remain locked.

Voice and up-data information to be transmitted to the CSM will be angle modulated onto subcarriers of 30 kc and 70 kc respectively. These subcarriers then will be phase modulated onto the PM up-carrier as shown in Figure 12.

Telemetry and voice information to be transmitted to the tracking station will be angle modulated onto subcarriers of 1.024 mc and 1.25 mc respectively. These subcarriers then will be phase modulated onto the PM down carrier as shown in Figure 13.

Allowable Carrier Interruption Time for Automatic Reacquisition

The allowable time that a carrier can be interrupted or absent and still have the loop pull into lock without outside assistance is affected by both the bandwidth of the narrow bandpass filter prior to the detector as stated earlier and the amount that the carrier, reduced to the IF frequency, is shifted from the center of the filter by Doppler as shown in Appendix C.

The equations that approximate the allowable carrier interruption times for the CSM carrier tracking loop of Figure 2 and for the ground station loop of Figure 2A are, respectively:

$$\tau_{au} \leqq T_1 \ln \left[\frac{1}{1 - \left[\frac{BW}{2} - Df\left(1 - \frac{220}{221}\right)\right]\left(\frac{1}{Df}\right)} \right] \tag{11}$$

τ_{au} = up-carrier interruption time

and

$$\tau_{ad} \leqq T_1 \left[\frac{1}{1 - \frac{1}{2}\left(\frac{BW}{Df}\right)} \right] \tag{12}$$

where τ_{ad} is the down-carrier interruption time and T_1, Df, and BW are as defined earlier.

The factor $Df\left(1 - \frac{220}{221}\right)$ in equation (11) is a result of the type of multiloop PLO used in the spacecraft receiver. The ground station equation (12) that includes a reference oscillator as shown in Figure 2A is simpler. When the down-carrier tracking loop is locked, the carrier, reduced to IF, is in the center of the bandpass filter.

The curve in Figure 14 shows the allowable carrier interruption time vs Doppler frequency shift for a 15 kc bandpass filter, corresponding to the CSM receiver tracking loop. For example, the allowable up-carrier interruption time (τ_{au}) for a Df of 77 kc experienced at translunar injection is about 0.12 seconds. An up-carrier interruption time of 0.22 seconds is allowed while in the earth parking orbit for a maximum Df of about 56 kc. Similar curves for the three filter time constants of the ground station receiver could be added to Figure 14. Instead, the curves in Figure 15 for allowable interruption time τ divided by the filter time constant T_1 are included to permit the allowable carrier interruption time to be determined for the loop filter time constants associated with either the 15 kc or 7 kc bandpass filters of Figures 2 and 2A. Since the LEM transponder contains no auxiliary oscillator the ground station will probably loose lock whenever the LEM carrier tracking loop looses lock.

Carrier Interruption Time That will Allow Subcarrier Acquisition

There is a possibility that the carrier tracking loop in the spacecraft receiver will acquire and track a up-subcarrier following an up-carrier interruption. Since the subcarrier intermodulations products of the 30 kc and 70 kc subcarrier are also present whenever both subcarriers are used on the up-link, there is also a possibility of tracking an intermod frequency especially the 40 kc product. This subcarrier or intermod product acquisition is possible because they are offset from the carrier less than the maximum Doppler frequency shift that may be encountered. There in no danger of down-subcarrier acquisition occurring on the down link because these subcarriers are offset by more than 1 mc. However, the up-subcarrier and intermod tones that are placed on the down link through the transponder turn-around channel could be acquired and tracked by the down carrier tracking loop. The up-subcarrier acquisition problem is treated here with the realization that the subcarrier and intermodulation tones are also a problem on the down links.

The tracking loop in the CSM or LEM will become unlocked if the PM carrier is interrupted. If the loop has been tracking a Doppler-shifted carrier that is interrupted, it will begin to return to the undisturbed loop frequency, f_o, as explained earlier and will sweep through the frequency band of the up-carrier spectrum. If the up-carrier returns while the tracking loop frequency is in the vicinity of a subcarrier, then the loop can possibly pull into lock and begin tracking a subcarrier. The addition of modulation to a subcarrier may cause the tracking loop to lose lock with the subcarrier if the phase changes are greater than can be followed by the tracking loop. Even though the loop is thrown out of lock by modulation, the tracking loop may remain in the vicinity of the subcarrier while it continues to be first pulled into lock then thrown out of lock by the modulated subcarrier. Thus, a 30 kc or 70 kc frequency error could be passed to the transmitter and PM demodulators of the spacecraft receiver and to the range code circuits of the ground receiver.

The up-carrier interruption time that will allow the voice and up-date subcarriers to be within the pull-in range of the up-carrier tracking loop can be approximated by the following equations, derived in Appendix D:

$$\tau_v \cong T_1 \ln \left[\frac{1}{1 - \left(V \pm \frac{BW}{2}\right)\left(\frac{1}{Df}\right)} \right] \tag{13}$$

$$\tau_{ud} \cong T_1 \ln \left[\frac{1}{1 - \left(UD \pm \frac{BW}{2}\right)\left(\frac{1}{Df}\right)} \right] \tag{14}$$

where

τ_v and τ_{ud} = carrier interruption time for the spacecraft tracking loop to drift within pull-in range of the voice or up-data subcarrier

V = voice subcarrier frequency (30 kc)

UD = up-data subcarrier frequency (70 kc)

BW = bandwidth of narrow bandpass filter

Df = Doppler shift at the time of carrier interruption

For example, if the CSM loop was tracking a 77 kc Doppler shifted up-carrier, f_1, that was interrupted for about 0.42 seconds, the loop would have returned 22.5 kc toward its undisturbed frequency. The tracking loop would then be within 7.5 kc or BW/2 of the f_1 ±30 kc voice subcarrier and would begin to pull into lock with the subcarrier. If the carrier was interrupted for 0.84 seconds, the loop would have returned 37.5 kc and would still be within the pull-in range of the f_1 ± 30 kc subcarrier. An interruption greater than 1.7 seconds would place the carrier tracking loop within the pull-in range of the $f_1 \pm 70$ kc up-data subcarrier (Figure 16). This 77 kc Doppler shift is possible at trans-lunar injection velocities.

The plot of carrier interruption time vs Doppler shift in Figure 17 shows the interruption time that can allow subcarrier acquisition. Any interruption time that falls within the ruled areas above a specific Doppler frequency shift will place either the 30 kc or 70 kc subcarrier within the pull-in range of the carrier tracking loop of the spacecraft receiver. Some type of alarm should be included in the ground station to detect and notify the operator that the spacecraft has acquired a subcarrier.

TOTAL INFORMATION OUTAGE TIME

The total time that any up-link channel is out will be the up-carrier interruption time plus the up-carrier tracking loop pull-in time. However, any up-carrier interruption will probably cause the ground station tracking loop to loose lock. Then, the up-link outage time must be added to equation 15 for the down-link to obtain the approximate outage time for any down-link channel.

The total time (T_o) that information in any down-link channel is lost is the total time that the down carrier is interrupted or lost, T_1, plus the pull-in time Tp_1 for the carrier tracking loop and Tp_2 for the demodulation loops of down-voice and down-telemetry channels. The following equation applies when the tracking loop automatically pulls back into phase lock.

$$T_o = T_1 + Tp_1 + Tp_2, \tag{15}$$

T_o should approximate the time that the voice and data circuits are out with $T_1 + Tp_1$ accounting for most of the outage time. The pull-in time Tp_2 for the demodulation loops with bandwidth sufficient to pass down-voice and down-telemetry should be small when compared with Tp_1 (probably in the millisecond range). Additional considerations are required for the range code circuits. It is presently understood that the range code loop must be re-locked by a procedure initiated by an attendant at the ground station after each carrier interruption sufficient to cause the loop to become unlocked.

If the carrier interruption is greater than the allowable interruption (equations 11 or 12), then equation (15) does not apply. The outage time is then the interruption time plus the manual or programmed acquisition time.

Carrier interruption time (T_i) will be controlled or determined, neglecting equipment failures, by the spacecraft maneuvers and omnidirectional antenna pattern nulls while in the near earth orbit. After the directional antenna is deployed, T_i will be determined primarily by spacecraft maneuvers. Any information outage time degrades the effectiveness of the unified S-band system. There is justification, therefore, for investigating methods for reducing the outage time.

PULL-IN TIME REDUCTION METHODS

There are several possible methods for reducing pull-in time which will reduce total information outage time. Several methods will be considered for reducing only the carrier tracking loop pull-in time. The reduction of pull-in time for the demodulating (not range code) loops will not be considered here since this time is relatively small compared to the carrier tracking loops due to greater $2B_\ell$ bandwidths.

Method 1. The ground station transmitter could be controlled or programmed so that the transmitted frequency would be offset to compensate for the Doppler frequency shift experienced at each segment of the spacecraft orbit covered by each ground station. The transmitter offset would not have to correspond to the exact Doppler shift but should be sufficient to place the received signal at the spacecraft within $\pm BW/2$ of the narrow bandpass filter in the carrier tracking loop. This procedure would maintain the VCO in the tracking loop of the spacecraft near its undisturbed oscillating frequency and would insure rapid pull-in after an up-carrier interruption.

The ground station receiver should also be controlled in the absence of a down-carrier so that the difference between the down-carrier frequency and the loop frequency (δf) is also less than $\pm BW/2$ of the narrow bandpass filter in the ground station carrier tracking loop. The tracking loop should be free to track the carrier but should be switched to the controlling program when the down carrier is interrupted. This switching could be controlled by a circuit that monitors the AGC voltage of the receiver. When the AGC voltage reached a certain level, the receiver tracking control could be switched to the programmed control.

The pull-in by this method would always be automatic and the pull-in range would be less than ±BW/2 which insures a short pull-in time. Once BW and B_ℓ are determined, the maximum pull-in time can be obtained from Figures 4 and 5.

Method 2. Information about the amount of static charge on the capacitor in the loop filter of the spacecraft carrier tracking loop could be monitored and transmitted to the ground station. The ground station transmitter could then be controlled to transmit a carrier off-set sufficient to maintain a near zero static charge on the capacitor.

The AGC voltage would also be monitored so that the transmitted frequency would not be changed during an up-carrier interruption. Information about the amount of transmitter shift could be used to control the ground station receiver similar to Method 1 in the absence of a down-carrier.

This method assumes that the change in Doppler frequency during a carrier interruption is within the pull-in range of the receiver tracking loops $\left(\leq \frac{BW}{2}\right)$. A manual or programmed acquisition procedure would be required for initial lock-up as the spacecraft enters the horizon of a tracking station.

Method 3. The ground station and spacecraft receiver could be modified by installing a sample and hold type circuit controlled by the AGC voltage in the receivers. This circuit could monitor the static charge on the capacitor in the loop filter. If the AGC voltage dropped below a level that indicated a loss of carrier, the sample and hold circuit would then maintain the last sampled static charge on the capacitor.

This method also assumes that the Doppler frequency change encountered during a carrier interruption is small. Thus, only the Doppler shift that occurred during the carrier interruption would have to be pulled in by the loop.

Method 4. The ground station and spacecraft tracking loops could be modified to include a frequency difference detector[9] as shown in Figure 18. The generated control voltages from the regular PLO loop detector and the frequency difference detector is represented in the drawing above the block diagram. The regular PLO would automatically pull-in to lock for any frequency difference less than BW/2 caused by a carrier interruption. The added frequency difference detector would produce a control voltage to pull the loop toward lock for frequency differences between BW/2 and the maximum Doppler shift experienced at any phase of the mission. When the frequency difference (δf) is brought to within ±BW/2 by the frequency difference detector, the regular PLO would gain control and pull the loop into lock. While the regular PLO loop is locked, the output error voltage from the frequency difference detector would be zero and thus would not degrade the regular PLO loop operation. The feasibility of connecting the difference detector output directly to the regular PLO modulator must be considered. Richman[9] considers it possible. This method could possibly eliminate manual or programmed carrier tracking loop lock procedures for S/N ratios greater than 10 db at the input to the frequency difference detector circuit.

There are, no doubt, many other methods that can be employed to reduce PLO pull-in time. After considering the four methods discussed here, the frequency difference detector method (Method 4) appears to be the easiest and possibly the least expensive to implement.

CONCLUDING REMARKS

PM carrier interruption can cause a number of problems with the present S-band system. Interruptions that occur while the spacecraft is in the near-earth trajectories where Doppler shifts are greatest are the most critical. Interruption for various time intervals, depending on the amount of Doppler shift experienced at the time of interruption, can allow the PLO loops to acquire and track an up-subcarrier which is undesirable or may require complete reacquisition procedures be initiated by a ground station.

The equations and curves for calculating pull-in time, allowable carrier interruption time, and subcarrier acquisition time emphasize the problems caused by carrier interruptions. Other equations are included to give a better understanding of PLO loop operation.

A quantitative evaluation of total information outage time cannot be made until specific information is available on spacecraft antenna patterns and maneuvers. Until this information is available, the material presented in this memorandum affords some appreciation for the problems caused by carrier interruptions and suggests several methods for reducing the time associated with reacquisition.

J. C. Lumsden

WH-4334-JCL-BWO J. C. LUMSDEN

Att.
References
Appendices A - D
Figures 1 - 18

REFERENCES

1. Painter, J. H., et al, Unified S-band Telecommunication Techniques for Apollo, Vol 1, NASA TN D-2208, Manned Spacecraft Center, Houston, Texas.

2. Byrne, C. J., Properties and Design of the Phase Controlled Oscillator with a Sawtooth Comparator, BSTJ, March 1962, pp. 559-602.

3. Viterbi, A. J., Phase Lock Loop Systems, Space Communications, McGraw-Hill, New York, 1963.

4. Weaver, C. S., A New Approach to the Linear Design and Analysis of Phase-Locked Loops, IRE Transactions on Space Electronics and Telemetry, December 1959, p. 178.

5. Viterbi, A. J., Acquisition and Tracking Behavior of Phase-Locked Loops, Proceedings of the Symposium on Active Networks and Feedback Systems, New York, 1960.

6. Richman, D., Color-Carrier Reference Phase Synchronization Accuracy in NTSC Color Television, Proceedings of the IRE, January 1954, pp. 106-133.

7. Nelson, W. L., Phase-Lock Loop Design for Coherent Angle Error Detection in Telstar Satellite Tracking System, BSTJ, September 1963, 1941-77.

8. Private communications from J. T. Raleigh, Bellcomm.

9. Gardner, F. M., et al, Theory of Phaselock Techniques as Applied to Aerospace Transponders - NASA Contract No. NAS 8-11509 - Huntsville, Ala.

10. Richman, D., The DC Quadircorrelator: A Two-Mode Synchronization System, Proceedings of the IRE, January 1954, pp. 288-99.

11. Private conversation from M. Brockman, JPL.

APPENDIX A

PLO Loop Noise Bandwidth

The equivalent two-sided noise bandwidth ($2B_\ell$) is by definition[5]

$$2B_\ell = \frac{1}{2\pi j}\int_{-j\infty}^{+j\infty} |\, G(s)\,|^2 \, ds \qquad \text{(A-1)}$$

where $G(s)$ is the closed loop transfer function of the linearized loop. The basis for this lies in the fact that a flat noise spectral density of magnitude Φ at the input of the linearized system will produce a noise power of $2\Phi B_\ell$ at the output. Thus, $2B_\ell$ is the bandwidth of the ideal square cutoff low-pass filter which produces the same amount of noise power at its output as does the linear system whose realizable transfer function is $G(s)$. With this definition, the loop noise bandwidth with various filters can be determined. The closed loop transfer function of the second order carrier tracking loops used in the Apollo system[1,9] is of the form

$$\frac{\Phi_o}{\Phi_i} = G(s) = \frac{\dfrac{G_oF(s)}{s}}{1 + \dfrac{GF(s)}{s}} = \frac{G_oF(s)}{s + GF(s)} \qquad \text{(A-2)}$$

where

Φ_i = input signal

Φ_o = output signal

G_o = open loop gain

and

$\frac{G_o}{s}$ reflects the integrating actions of the reactance modulator and oscillator that converts the driving signal voltage to an output sinusoidal signal with a constant amplitude and varying phase

F(s) = loop filter transfer function of Figure 1

$$F(s) = \frac{R_2}{R_1 + R_2} \; \frac{s + \frac{1}{R_2 C}}{s + \frac{1}{(R_1+R_2)C}} = G_f \frac{[s-Z]}{[s-P]} \tag{A-3}$$

where

$$G_f = \frac{R_1}{R_1 + R_2}$$

$$s = j\omega.$$

The closed loop transfer function is then

$$G(s) = \frac{\frac{G_o G_f [s-Z]}{[s-P]}}{s + \frac{G_o G_f [s-Z]}{[s-P]}} = \frac{G_o G_f [s-Z]}{s[s-P] + G_o G_f [s-Z]} \,. \tag{A-4}$$

$$G(s) = \frac{G_o G_f [s-Z]}{s^2 + s[G_o G_f - P] - G_o G_f Z} \,. \tag{A-5}$$

A total gain constant, G_T, can be defined:

$$G_T = G_o G_f \ .$$

Then

$$G(s) = G_T \left[\frac{s - Z}{s^2 + s[G_T - P] - G_T Z} \right] . \qquad \text{(A-6)}$$

The denominator of the transfer function is of the form common to servo systems

$$s^2 + 2K\omega_n s + \omega_n^2 = s^2 + s(G_T - P) - G_T Z \qquad \text{(A-7)}$$

where $\omega_n = \sqrt{-G_T Z}$ is the undamped natural frequency of oscillation of the loop. ω_n is not the frequency ω_o of the VCO itself but describes the rate at which the system would oscillate about the VCO frequency if the transfer function resistance was zero. ω_n also describes the optimum rate that the VCO should be varied by an outside force if the VCO is to be swept through a frequency band to expedite signal acquisitions by the PLO loop.

$K = \dfrac{G_T - P}{2\sqrt{-G_T Z}}$ is the loop damping ratio. $G(s)$ is then

$$G(s) = \frac{(2K\omega_n + P)s + \omega_n^2}{s^2 + 2K\omega_n s + \omega_n^2}$$

since P is small when compared with $2K\omega_n$

$$G(s) = \frac{2K\omega_n s + \omega_n^2}{s^2 + 2K\omega_n s + \omega_n^2} \, . \tag{A-8}$$

The equivalent two-sided noise bandwidth is then determined by integration to be

$$2B_\ell = \frac{\omega_n(1+4K^2)}{4K} \tag{A-9}$$

APPENDIX B

Effect of Limiter on PLO Loop Noise Bandwidth and Pull-in Time

The signal voltage at the output of a limiter varies according to the limiter suppression factor "α", where[9]

$$\alpha \approx \left[\frac{1}{\frac{4}{\pi \, (S/N)_{input}} + 1} \right]^{1/2} \tag{B-1}$$

This relation is plotted in Figure 4.

Minimum noise bandwidth will occur at minimum signal levels in any particular loop. This minimum signal is usually specified as the threshold and will be designated here with the subscript "[illegible] ise bandwidth B_ℓ may then be exp[illegible] as

$$B_\ell \approx B_{th} \frac{\left[\frac{\alpha}{\alpha_{th}} + \frac{1}{4K_{th}^2} \right]}{\left[1 + \frac{1}{4K_{th}^2} \right]} \tag{B-2}$$

where

B_{th} = threshold noise bandwidth

α_{th} = threshold limiter suppression factor

K_{th} = loop damping factor at design threshold

When the design threshold damping factor K is 0.707,

$$B_\ell \cong \frac{B_{th}}{3}\left(2\,\frac{\alpha}{\alpha_{th}} + 1\right) \qquad \text{(B-3)}$$

α and α_{th} may be obtained from Figure 4.

In general pull-in time may then be estimated for any bandwidth above threshold by obtaining α corresponding to a particular S/N ratio above threshold from Figure 4 and solving the following equation derived by Richardson[6] which has been modified to include the action of the bandpass limiter.

$$T_p \approx \left[\frac{\pi(df)}{2\left(K_{th}\sqrt{\frac{\alpha}{\alpha_{th}}}\right)^2}\right]^2 \left[\frac{K_{th}^2 + \frac{1}{4}}{B_{th}}\right]^3 \qquad \text{(B-4)}$$

or

$$T_p \cong \left[\frac{\pi(\delta f)}{2\left(K_{th}\sqrt{\frac{\alpha}{\alpha_{th}}}\right)^2}\right]^2 \left[\frac{\left(K_{th}\sqrt{\frac{\alpha}{\alpha_{th}}}\right)^2 + \frac{1}{4}}{B_\ell}\right]^3$$

(B-5)

APPENDIX C

Allowable Carrier Interruption Time vs Doppler Shift

The carrier tracking loops of Figures 2 and 2A are used to develop equations to approximate the allowable carrier interruption time when a narrow band filter is included in front of the limiter.

The received carrier at the spacecraft (Figure 2) without modulation is represented by

$$M_o = A \cos(\omega_c t \pm Df) \qquad \text{(C-1)}$$

where

Df = Doppler shift

ω_c = ground station transmitting radian frequency

The VCO output can be described by

$$M_1 = \cos(\omega_{vco} t + 2\theta) \qquad \text{(C-2)}$$

where 2θ is a reference phase (or frequency). The input to the detector from the VCO is divided by 2 and shifted 90 degrees in phase

$$M_2 = \cos\left(\frac{\omega_{vco} + \pi + 2\theta}{2}\right) \qquad \text{(C-3)}$$

$$M_2 = -\sin\left(\frac{\omega_{vco} t}{2} + \theta\right) \qquad \text{(C-4)}$$

The input to the second mixer from the VCO is

$$M_3 = \cos(2\omega_{vco}t + 4\theta) \quad \text{(C-5)}$$

The input to the first mixer from the VCO is

$$M_4 = \cos(108\omega_{vco}t + 216\theta) \quad \text{(C-6)}$$

The input to the first IF is the lower product of $(M_o)(M_4) = M_5$

$$M_5 = G_1\cos(\omega_{IF1}t \pm Df - 216\theta) \quad \text{(C-7)}$$

where G is the combined gain constants. The input to the second IF and to the narrow bandpass filter is then

$$M_6 = G_2\cos(\omega_{IF2} \pm Df - 216\theta - 4\theta) \quad \text{(C-8)}$$

or

$$M_6 = G_2\cos(\omega_{IF2}t \pm Df - 220\theta) \quad \text{(C-9)}$$

The phase detector output is then

$$M_7 = G_3\sin(\pm Df - 221\theta) \quad \text{(C-10)}$$

When the loop is locked and tracking the carrier, $\sin(\pm Df-221\theta)$ must be small or $\sin(\pm Df-221\theta) \cong \pm Df - 221\theta$ so that

$$\theta \cong \frac{\pm Df}{221} \quad \text{(C-11)}$$

Thus, the VCO is shifted by 2θ when the loop is locked and tracking a Doppler shifted carrier. The phase detector output is then:

$$M_7 \cong G \sin\left[\pm Df - 221\left(\frac{\pm Df}{221}\right)\right] \qquad (C-12)$$

$$\cong G \sin\left[Df\left(1 - \frac{221}{221}\right)\right]$$

$$\cong 0$$

Assume that both Df and θ are expressed in cycles. If the carrier was not shifted by Doppler and the loop was locked, then there would be no loss in assuming that both Df and θ are zero. Further, the amount of any Doppler shift encountered by the carrier is reduced by loop tracking action before it reaches the narrow bandpass filter in the second IF (M_6). The input signal to the second IF and narrow bandpass filter is then shifted from the center of the filter by an amount much less than the actual Doppler shift. The amount of off-center (OC) or shift from the center of the filter is derived by substituting $\theta = \pm Df/221$ into equation M_6

$$M_6 \cong G \cos\left[\omega_{IF2}t \pm Df - 220\left(\pm \frac{Df}{221}\right)\right]$$

$$\cong G \cos\left[\omega_{IF2}t \pm Df\left(1 - \frac{220}{221}\right)\right] \qquad (C-13)$$

Thus

$$OC \cong \pm Df\left(1 - \frac{220}{221}\right) \qquad (C-14)$$

$$|\,OC\,| = Df\left(1 - \frac{220}{221}\right)$$

$$|\,OC\,| = 4.5249\times10^{-3}\ Df$$

or $|\,OC\,|$ is less than 400 cps for the maximum up-carrier Doppler shift expected. This shift from the center of the bandpass filter reduces the allowable carrier interruption time since the loop has a smaller range to drift before δf becomes greater than BW/2.

In general, the allowable time (τ_{au}) that the up-carrier can be interrupted and still have the loop automatically pull back into lock can be derived by referring to the equation for δf

$$\delta f \cong Df\left(1 - e^{-\frac{\tau}{T_1}}\right) \tag{C-15}$$

where, in this case, δf is the amount of drift allowed before the input to the second IF is out of the range of the narrow bandpass filter.

τ is then:

$$\tau \cong T_1\ \ln\left[\frac{1}{1 - \frac{\delta f}{Df}}\right] \tag{C-16}$$

where

$$\delta f \leqq \left(\frac{BW}{2} - OC\right) \tag{C-17}$$

$$\delta f \leqq \left[\frac{BW}{2} - Df\left(1 - \frac{220}{221}\right)\right] \tag{C-18}$$

$$\left[\frac{BW}{2} - Df\left(1 - \frac{220}{221}\right)\right] \geqq Df\left(1 - e^{-\frac{\tau_{au}}{T_1}}\right) \qquad (C-19)$$

$$\tau_{au} \leqq T_1 \ln\left[\frac{1}{1 - \left[\frac{BW}{2} - Df\left(1 - \frac{220}{221}\right)\right]\left(\frac{1}{Df}\right)}\right] \qquad (C-20)$$

where τ_{au} is the allowable up-carrier interruption time. A similar analysis for the ground station receiver of Figure 2A shows that the input to the narrow bandpass filter is always within one-fourth of a cycle from the center of the filter while the loop is locked. Therefore, the allowable δf is approximately equal to BW/2 and

$$\tau_{ad} \leqq T_1 \ln\left[\frac{1}{1 - \frac{1}{2}\left(\frac{BW}{Df}\right)}\right] \qquad (C-21)$$

where τ_{ad} is the allowable down carrier interruption time.

APPENDIX D

Possible Subcarrier Acquisition by Carrier Tracking PLO

This appendix is an extension of Appendix C where equations for carrier reacquisition time were developed. Subcarrier acquisition by the up-carrier tracking PLO loop in the CSM receiver is possible under certain Doppler and carrier interruption conditions. The up-carrier interruption time for subcarrier acquisition will be greater than for carrier reacquisition because the loop frequency must change sufficiently to place the voice or up-data subcarrier within the pull-in range of the tracking loop or within BW/2 of a subcarrier when a narrow bandpass filter is included in the loop.

Equations (18), (19), and (20) of Appendix C can be modified to approximate the interruption time for subcarrier acquisition. Thus, the difference δf_v between the loop frequency input to the first mixer and the voice and up-data subcarrier is

$$\delta f_v \leqq V \pm \left[\frac{BW}{2} - Df\left(1 - \frac{220}{221}\right)\right] \qquad \text{(D-1)}$$

$$\delta f_{ud} \leqq UD \pm \left[\frac{BW}{2} - Df\left(1 - \frac{220}{221}\right)\right] \qquad \text{(D-2)}$$

as shown in Figure 16.

Equation (20) of Appendix C then becomes, for the voice subcarrier,

$$\tau_v \cong T_1 \ln\left[\frac{1}{1 - \left\{V \pm \left[\frac{BW}{2} - Df\left(1 - \frac{220}{221}\right)\right]\right\}\left(\frac{1}{Df}\right)}\right] \qquad \text{(D-3)}$$

and for the data subcarrier,

$$\tau_{ud} \cong T_1 \ln \left[\frac{1}{1 - \left\{ UD \pm \left[\frac{BW}{2} - Df \left(1 - \frac{220}{221} \right) \right] \right\} \left(\frac{1}{Df} \right)} \right] \qquad \text{(D-4)}$$

Since the factor $Df \left(1 - \frac{220}{221} \right)$ is less than 400 cycles for the maximum Doppler shift expected for an up-carrier frequency of 2.1064 gc, equations (3) and (4) reduce to

$$\tau_{v} \cong T_1 \ln \left[\frac{1}{1 - \left(V \pm \frac{BW}{2} \right) \left(\frac{1}{Df} \right)} \right] \qquad \text{(D-5)}$$

$$\tau_{ud} \cong T_1 \ln \left[\frac{1}{1 - \left(UD \pm \frac{BW}{2} \right) \left(\frac{1}{Df} \right)} \right] \qquad \text{(D-6)}$$

where

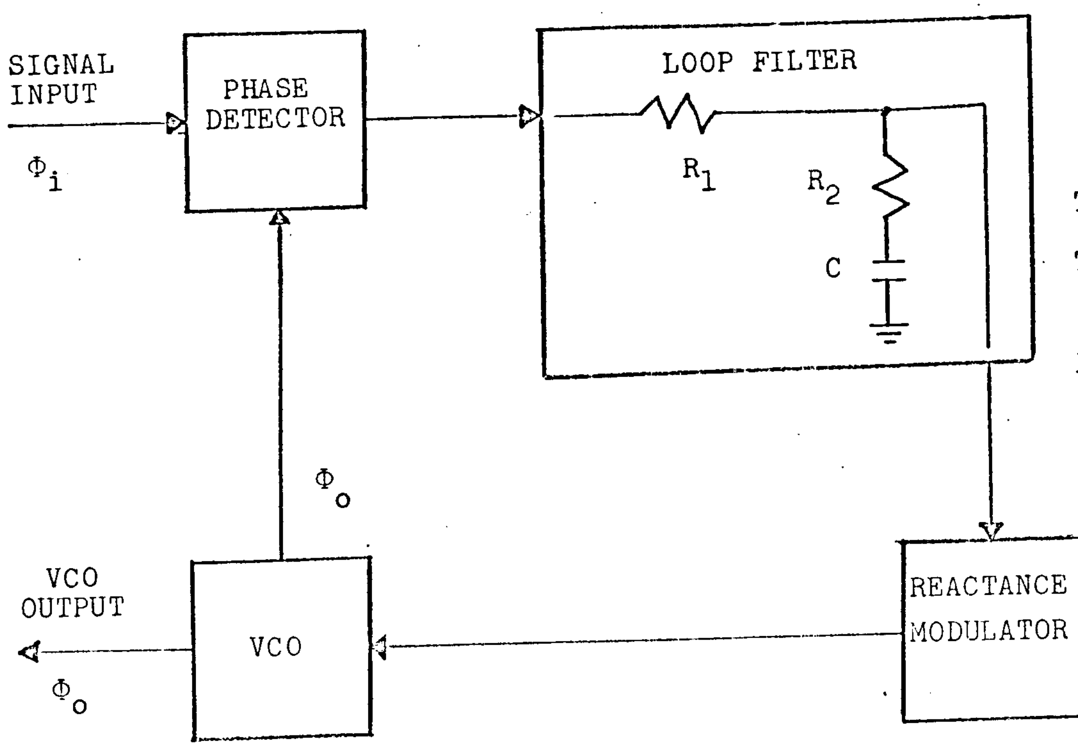
τ_v and τ_{ud} = carrier interruption time for the spacecraft tracking loop to drift within pull-in range of the voice or up-data subcarrier

V = voice subcarrier frequency (30 kc)

UD = up-data subcarrier frequency (70 kc)

BW = bandwidth of narrow bandpass filter in carrier tracking loop

Df = Doppler shift at the time of carrier interruption



$$T_1 = (R_1 + R_2)\,C$$

$$T_2 = R_2\,C$$

$$F(S) = \frac{R_2\,(S + 1/T_2)}{(R_1 + R_2)(S + 1/T_1)}$$

BASIC PHASE-LOCKED OSCILLATOR (PLO) LOOP

FIGURE 1

ISSUE

ENGR

DRAWN

TITLE BASIC PHASE-LOCKED OSCILLATOR LOOP FIGURE 1

BELL TELEPHONE LABORATORIES INCORPORATED

SHEET

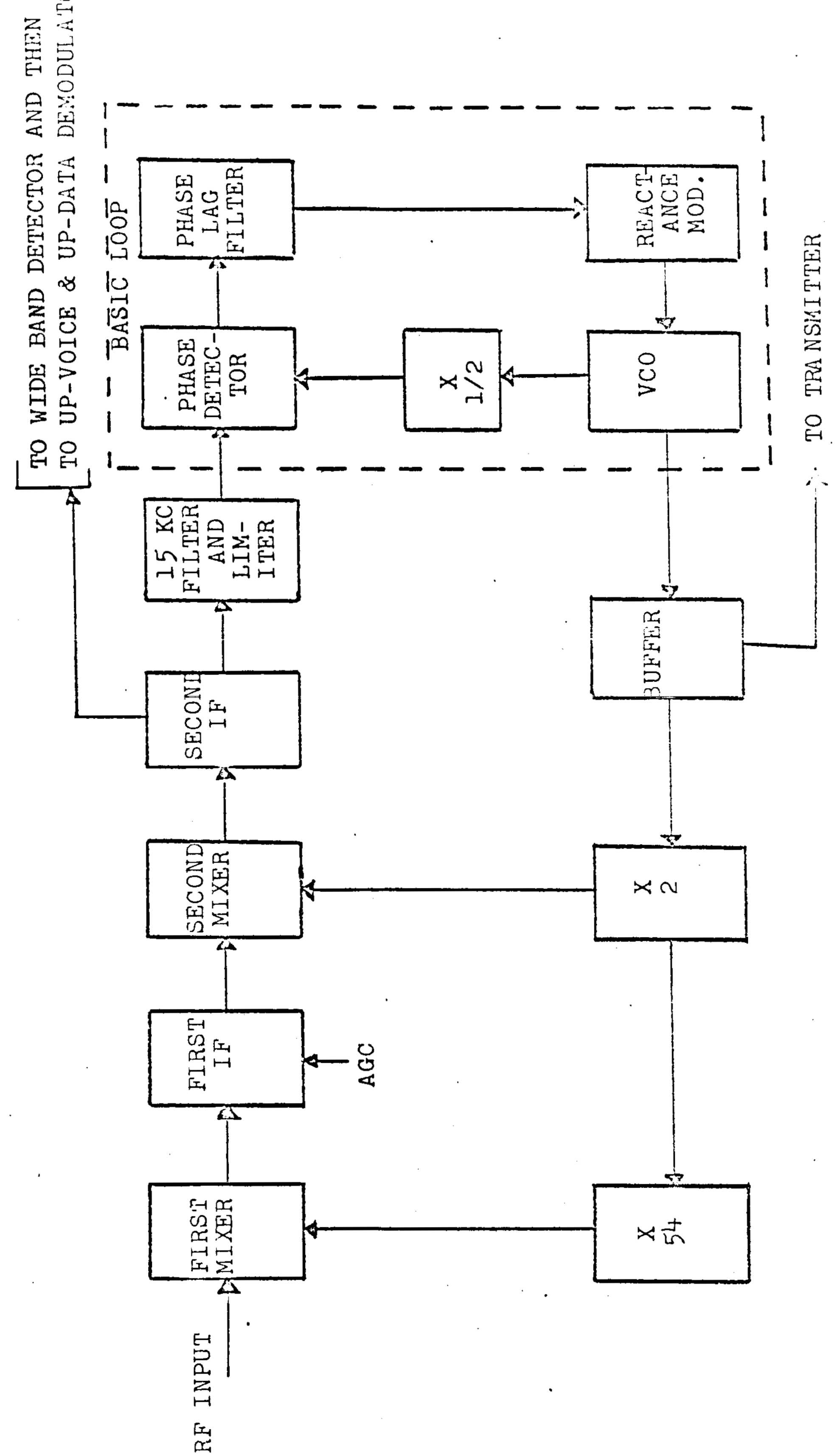
NO. OF SHEETS PER SET

PRINTED IN U.S.A E-1812-A-3 (2-61)

OGILVIE PRESS, INC. - C16

$10\frac{5}{8}$

$7\frac{11}{16}$



CSM CARRIER TRACKING PLO LOOP

FIGURE 2

ISSUE	ENGR	TITLE	BELL TELEPHONE LABORATORIES INCORPORATED
	DRAWN	CSM CARRIER TRACKING PLO LOOP FIGURE 2	SHEET / NO. OF SHEETS PER SET

PRINTED IN U.S.A. E-1812-A-3 (2-61)
OGILVIE PRESS, INC. - C16

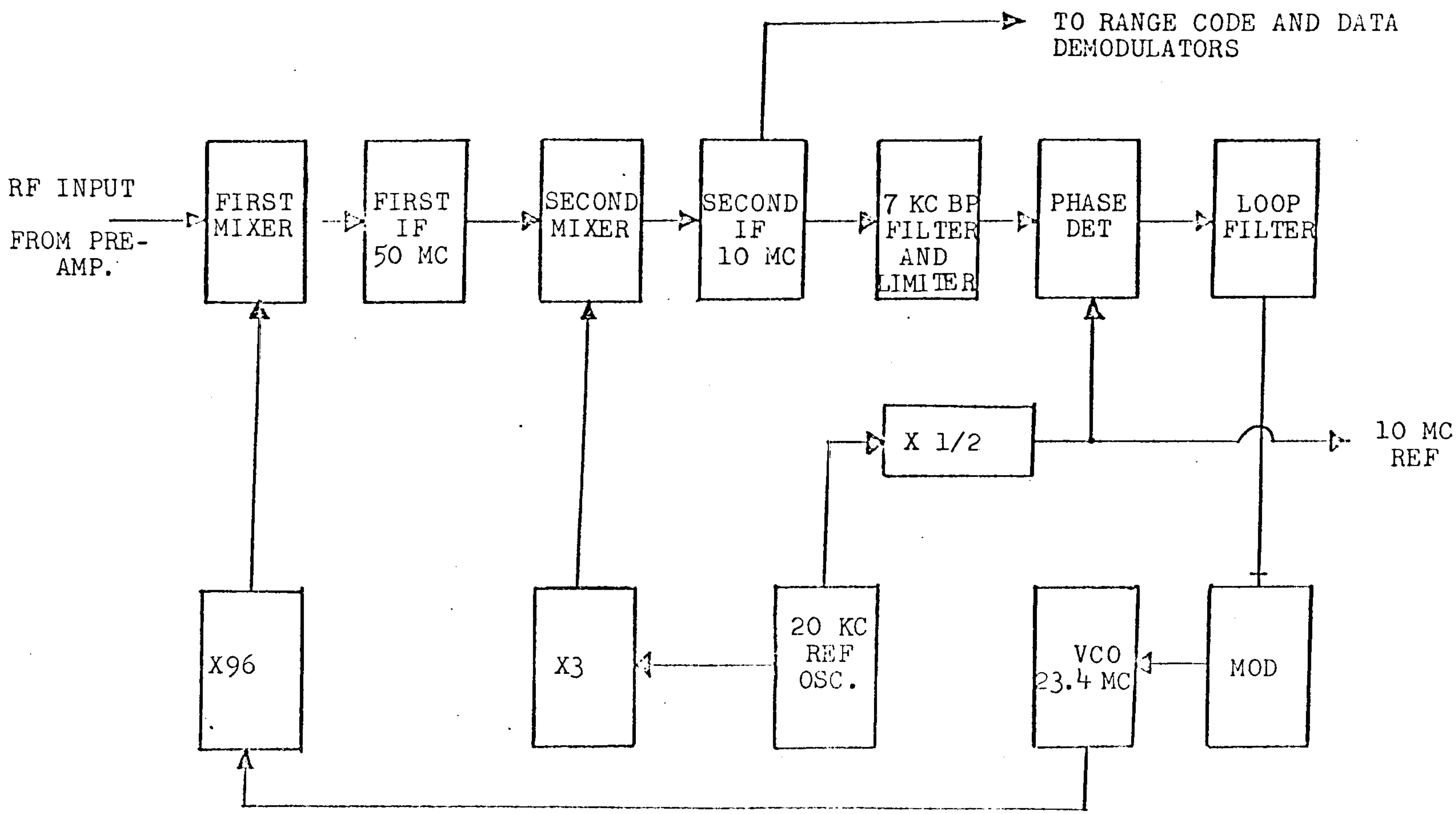


FIGURE 2A GROUND STATION DOWN-CARRIER TRACKING PLO LOOP

ISSUE	ENGR	TITLE	BELL TELEPHONE LABORATORIES INCORPORATED
	DRAWN	FIGURE 2A GROUND STATION DOWN-CARRIER TRACKING PLO LOOP	NO. OF SHEETS PER SET / SHEET

PRINTED IN U.S.A
E-1812-A-3 (2-61)
OGILVIE PRESS, INC. - C16

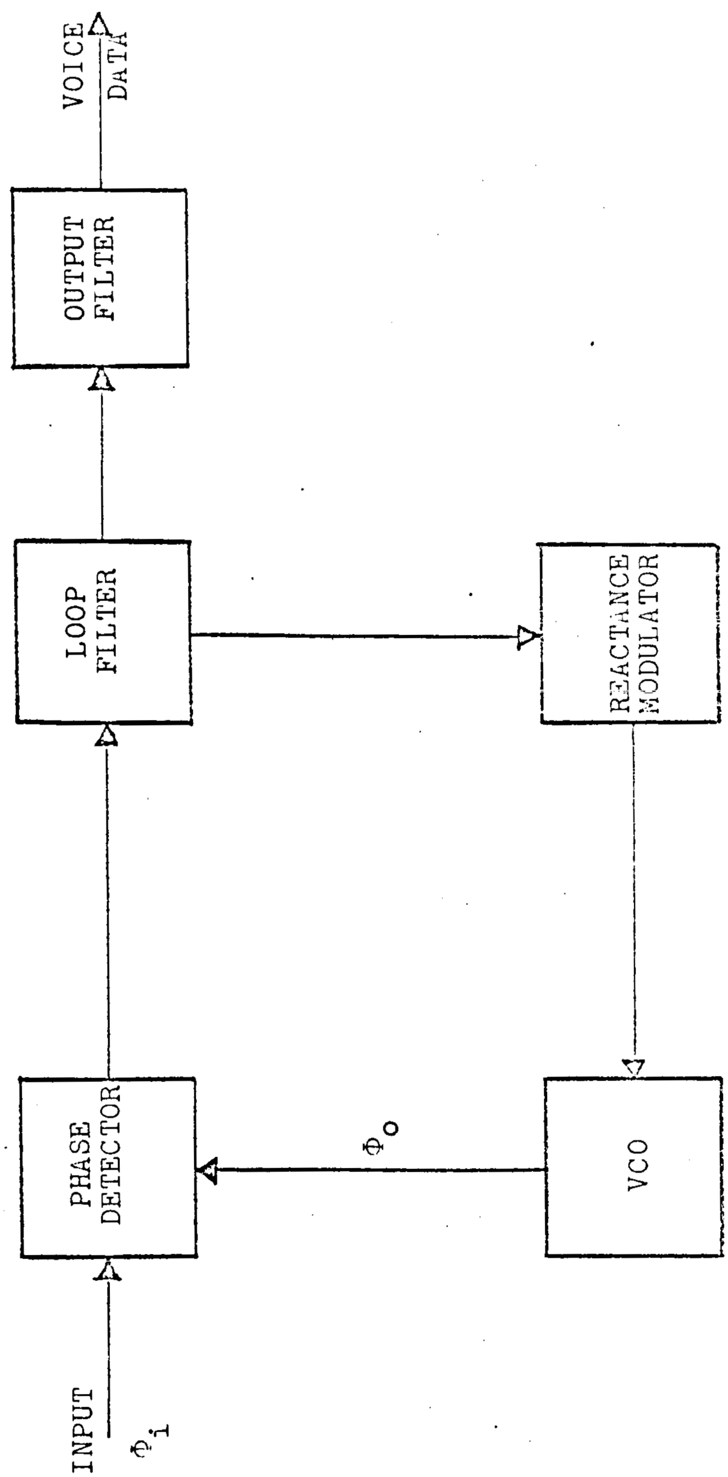
ISSUE

$10\frac{5}{8}$ $7\frac{11}{16}$

7 11/16

10 5/8

ISSUE



MODULATION TRACKING PLO LOOP

FIGURE 3

ISSUE	ENGR / DRAWN	TITLE	BELL TELEPHONE LABORATORIES INCORPORATED
		MODULATION TRACKING PLO LOOP FIGURE 3	NO. OF SHEETS PER SET / SHEET

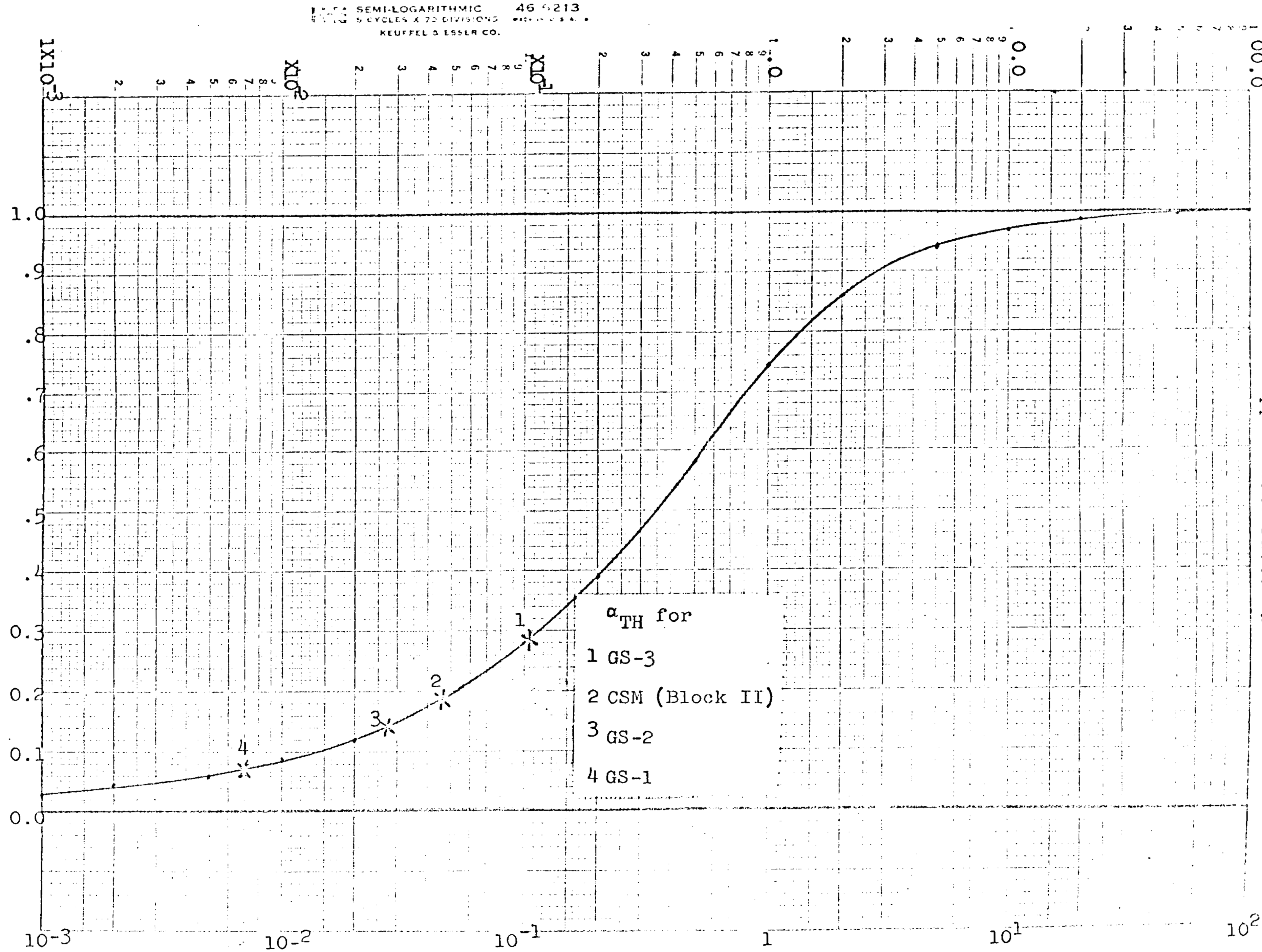


Figure 4 - Limiter Input Signal-to-Noise Ratio

K&E LOGARITHMIC 3 X 5 CYCLES 46 7522
KEUFFEL & ESSER CO.

Spacecraft carrier tracking loop characteristics for signal-to-noise ratios in the loop $(S/N)_L$ of 6 and 12 db.

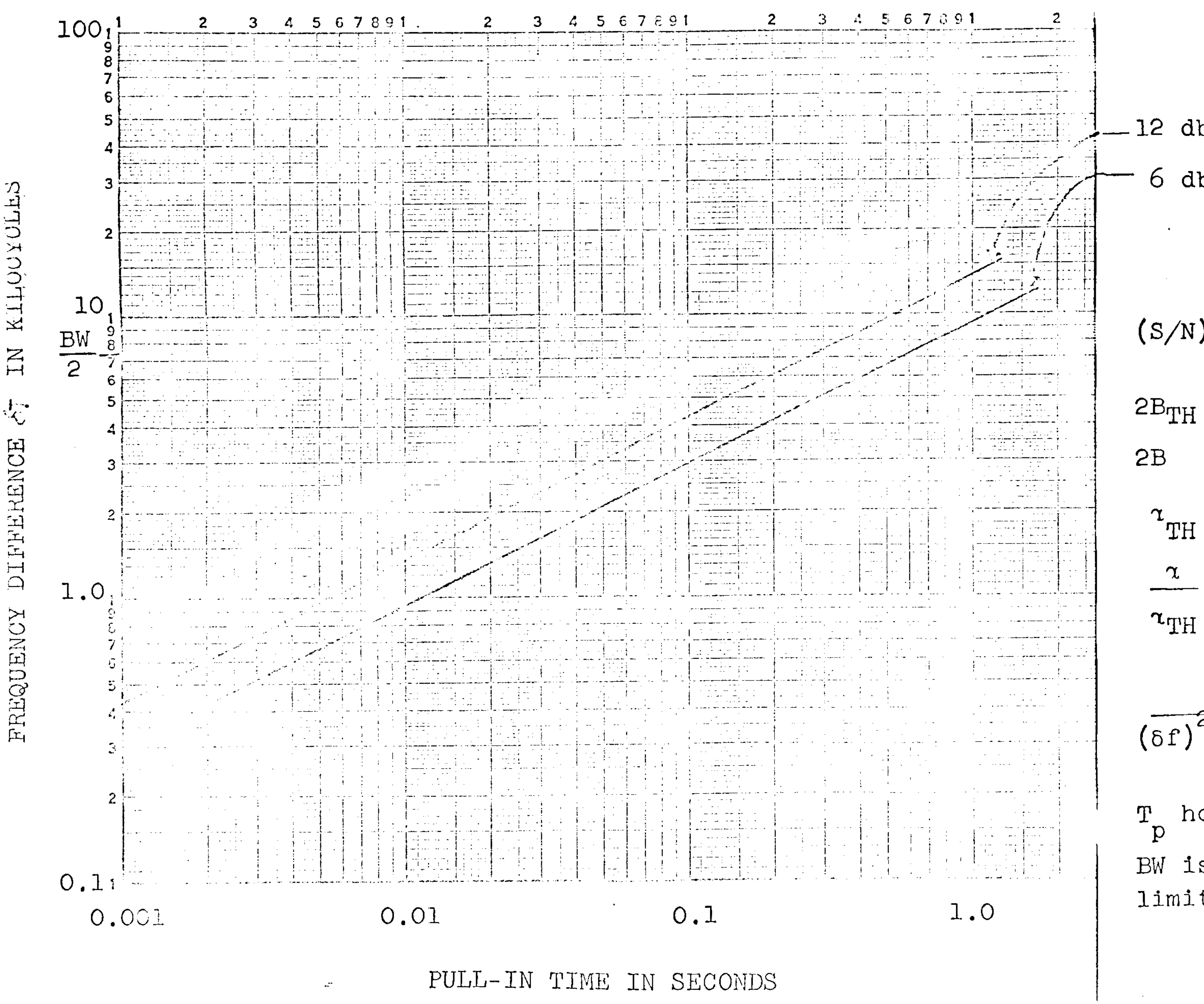
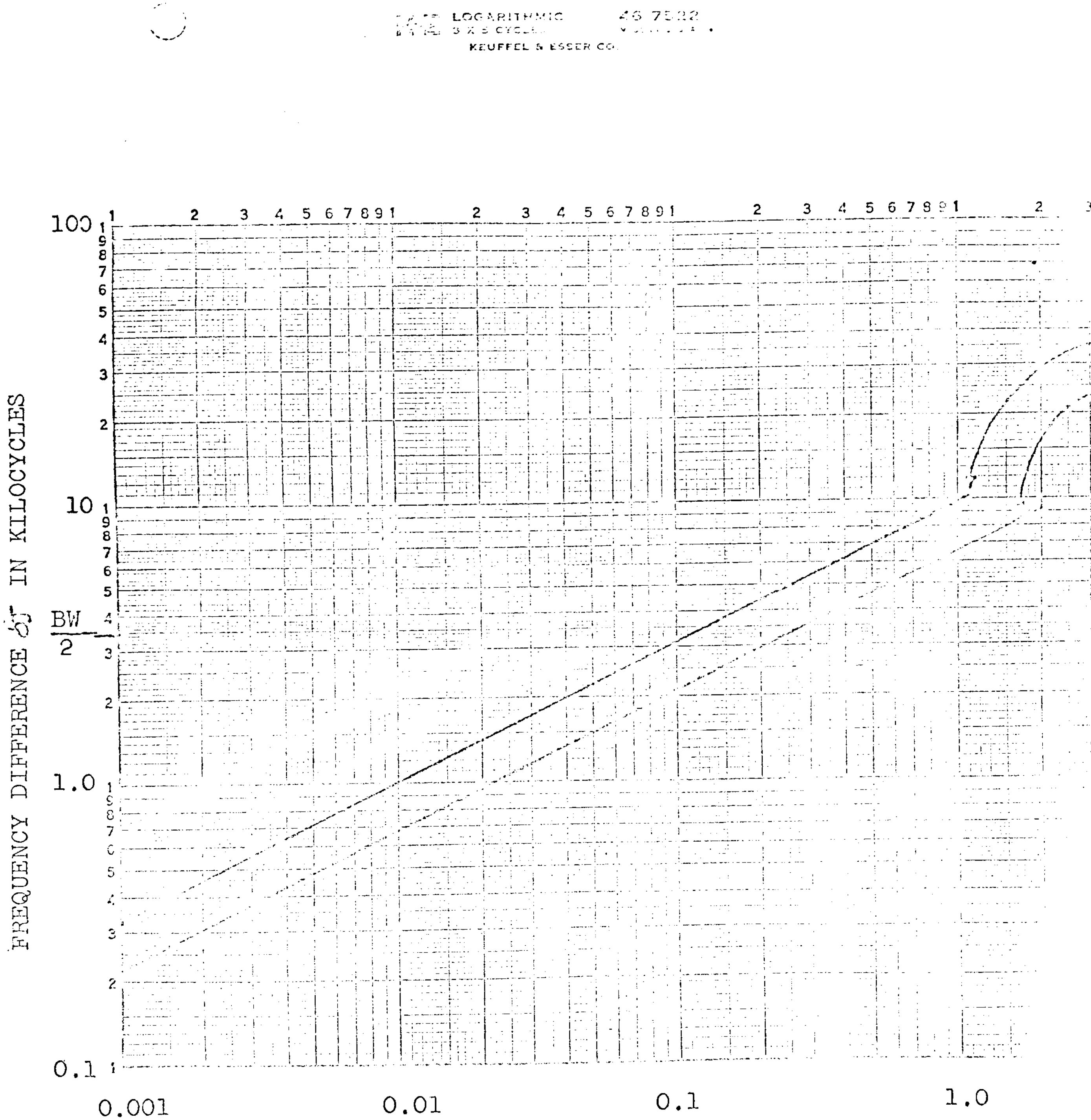


FIGURE 5

CSM (Block II)

$(S/N)_L$	6	12	db
$2B_{TH}$	700	700	CPS
$2B$	1575	2275	CPS
τ_{TH}	0.188	0.188	
$\frac{\tau}{\tau_{TH}}$	2.88	4.39	
$\frac{T_p}{(\delta f)^2 \times 10^{-8}}$	$\cong 1.17$	$\cong 0.58$	sec.

T_p holds for δf less than $\frac{BW}{2}$ where BW is the bandwidth of the bandpass limiter.



PULL-IN TIME IN SECONDS

FIGURE 6

Ground Station Characteristics, for signal-to-noise ratios in the tracking loop $(S/N)_L$ of 6 and 12 db.

GS-3

$(S/N)_L$ db	6	12	db
$2B_{TH}$	700	700	CPS
$2B_L$	1190	1640	CPS
α_{TH}	0.282	0.282	
$\frac{\alpha}{\alpha_{TH}}$	2.05	3.1	
$\frac{T_p'}{(\delta f)^2 \times 10^{-8}}$	$\cong 2.31$	$\cong 1.01$	sec.

T_p holds for δf less than $\frac{BW}{2}$ where BW is the bandwidth of the bandpass limiter.

PRINTED IN U.S.A
E-1812-A-3 (2-61)

$10\frac{5}{8}$

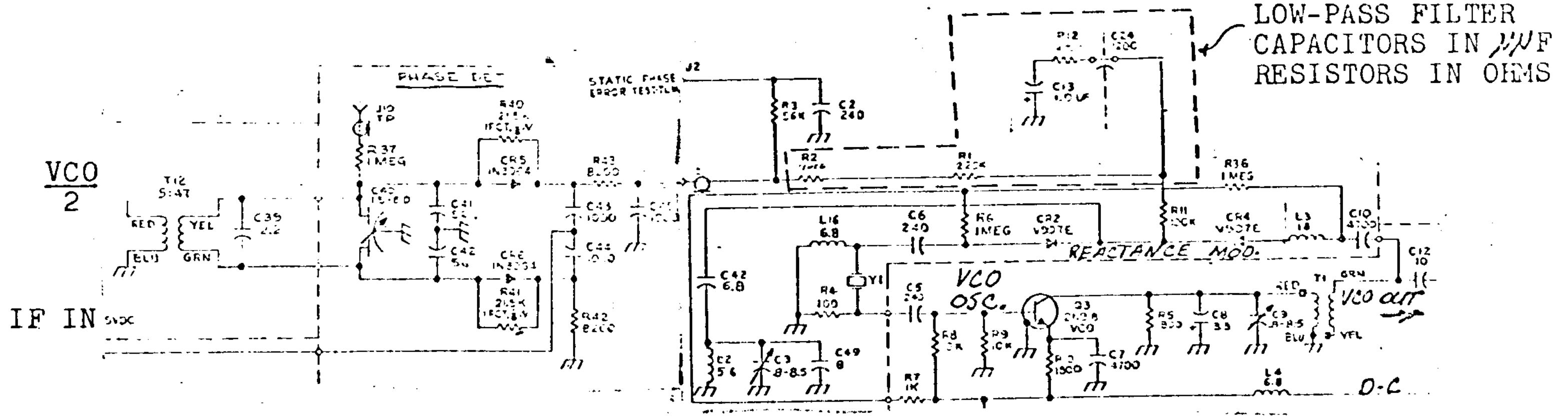


FIGURE 7 POSSIBLE CSM TRACKING LOOP PHASE-DETECTOR, MODULATOR, AND OSCILLATOR

$7\frac{11}{16}$

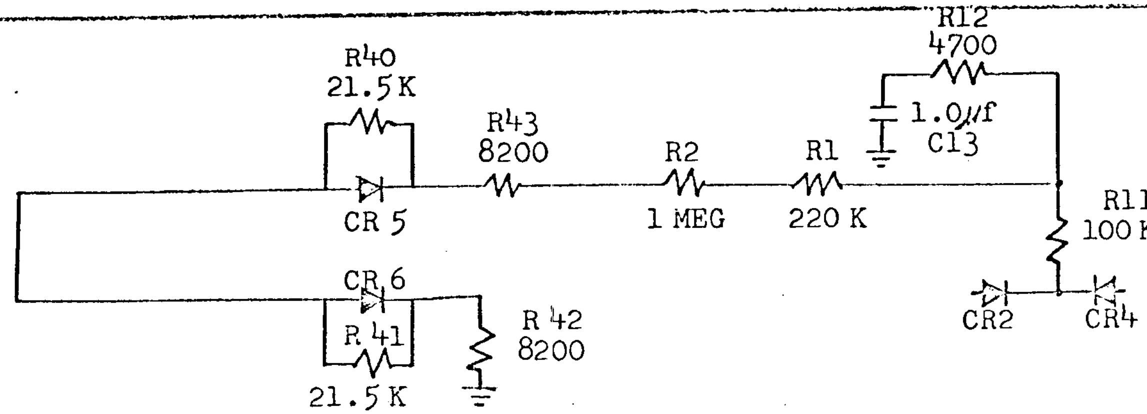


FIGURE 8 EQUIVALENT CIRCUIT OF FIGURE 4 WITH NO IF INPUT SIGNAL

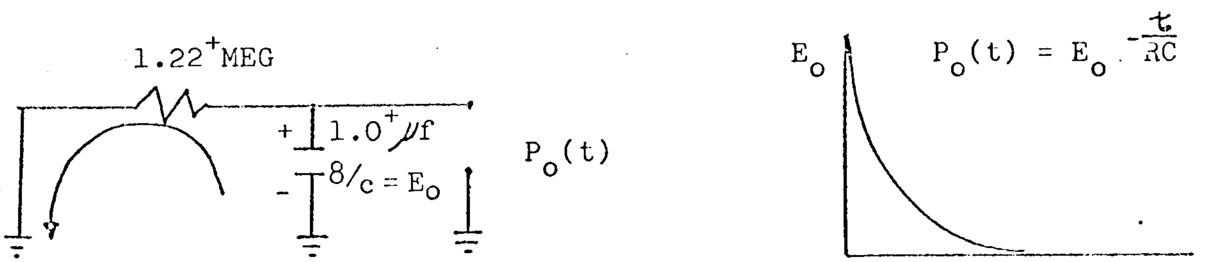
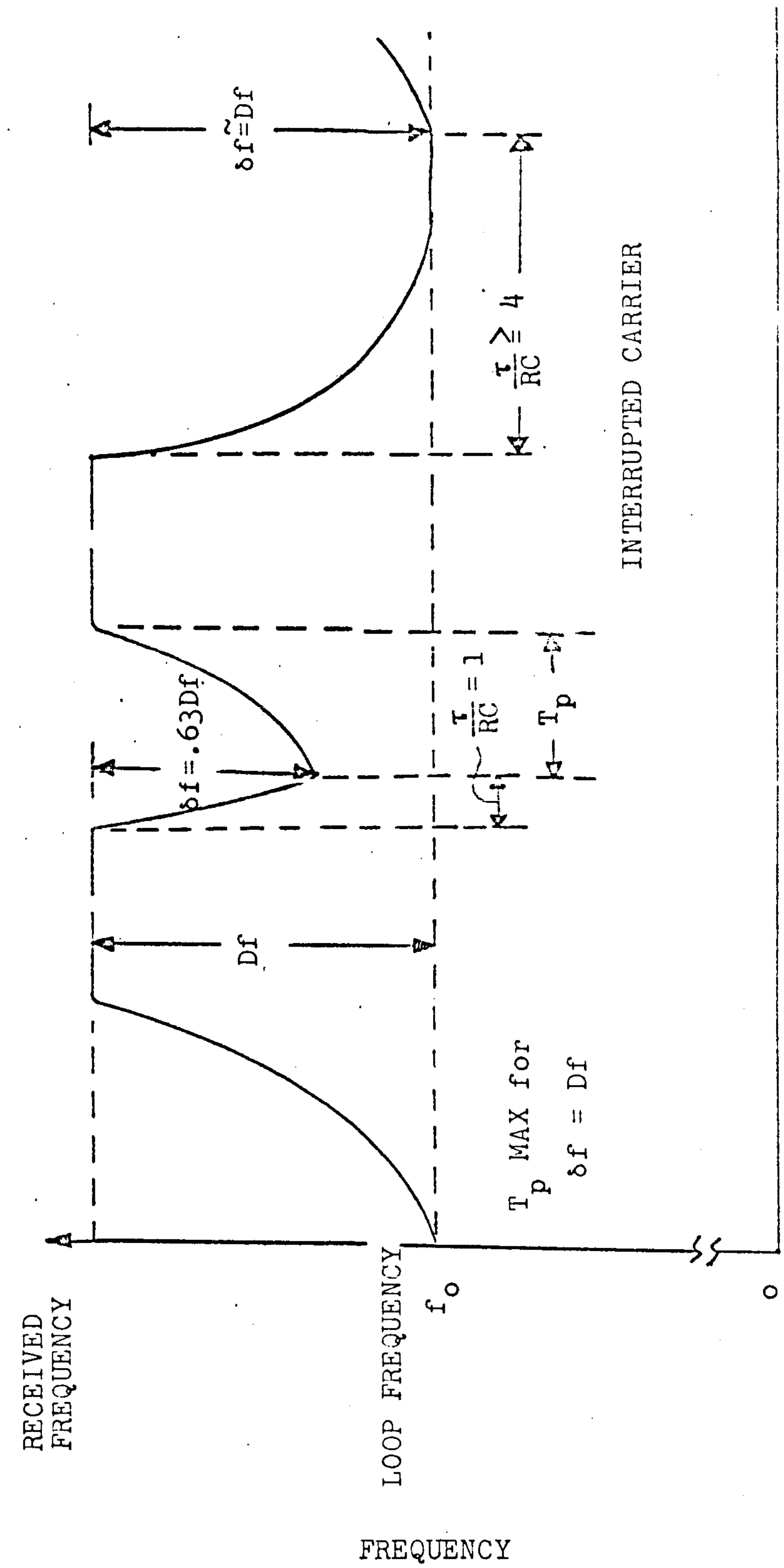


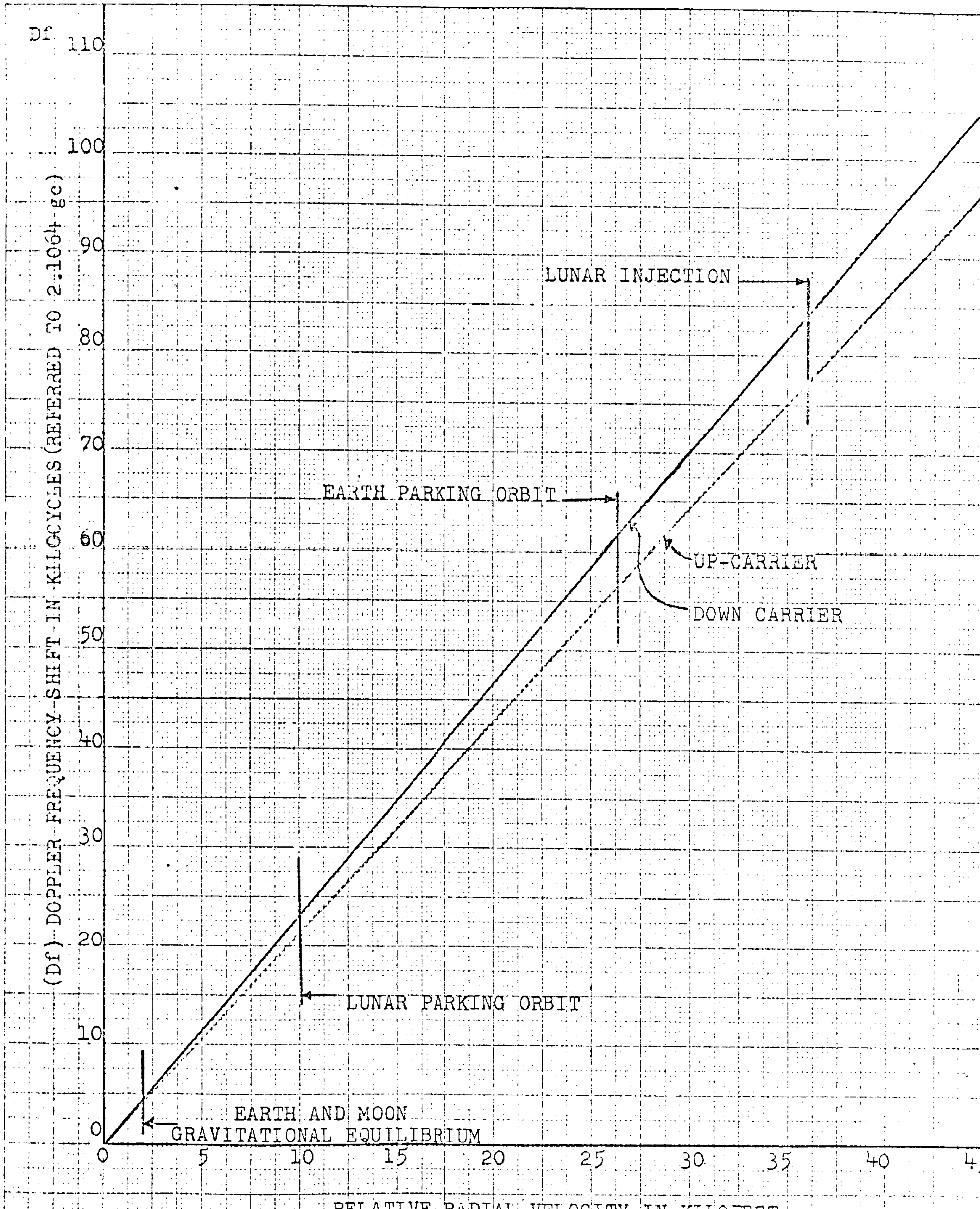
FIGURE 9 $P_o(t)$ - REACTANCE MODULATOR DRIFT RATE CONTROL VOLTAGE

ISSUE | ENGR | DRAWN | TITLE
BELL TELEPHONE LABORATORIES INCORPORATED
SHEET
NO. OF SHEETS PER SET
OGILVIE PRESS, INC. - C16



EFFECTS OF CARRIER INTERRUPTION TIME ON FREQUENCY DIFFERENCE (δf)

FIGURE 10



Df
(Df) DOPPLER FREQUENCY-SHIFT IN KILOCYCLES (REFERRED TO 2.1064 gc)
110
100
90
80
70
60
50
40
30
20
10
0
LUNAR INJECTION
EARTH PARKING ORBIT
UP-CARRIER
DOWN CARRIER
LUNAR PARKING ORBIT
EARTH AND MOON
GRAVITATIONAL EQUILIBRIUM
0
5
10
15
20
25
30
35
40
45
RELATIVE RADIAL VELOCITY IN KILOFEET

FIGURE 11

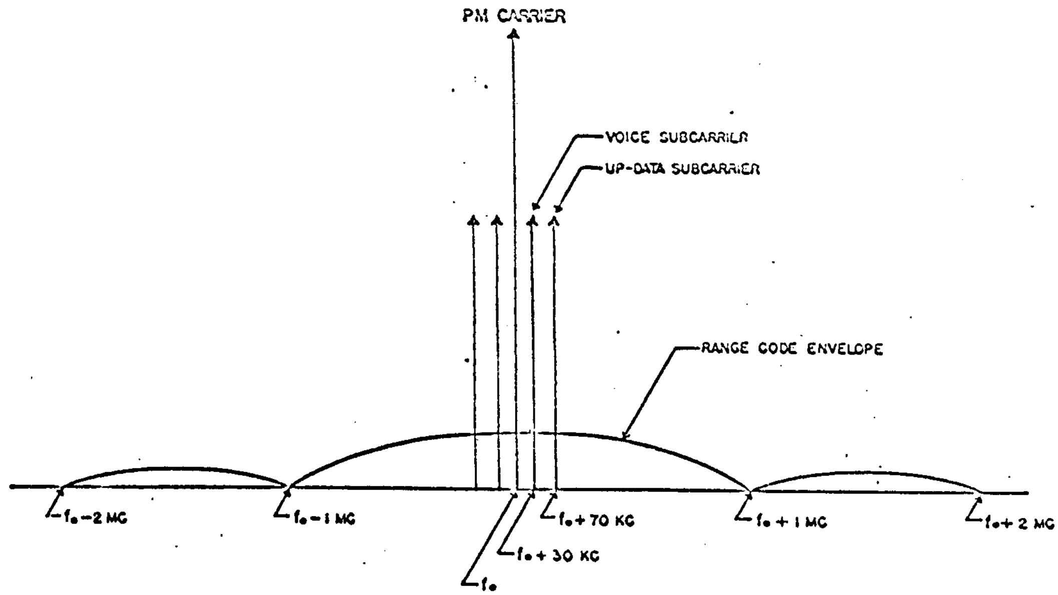


Figure 12 - Up-link to CSM

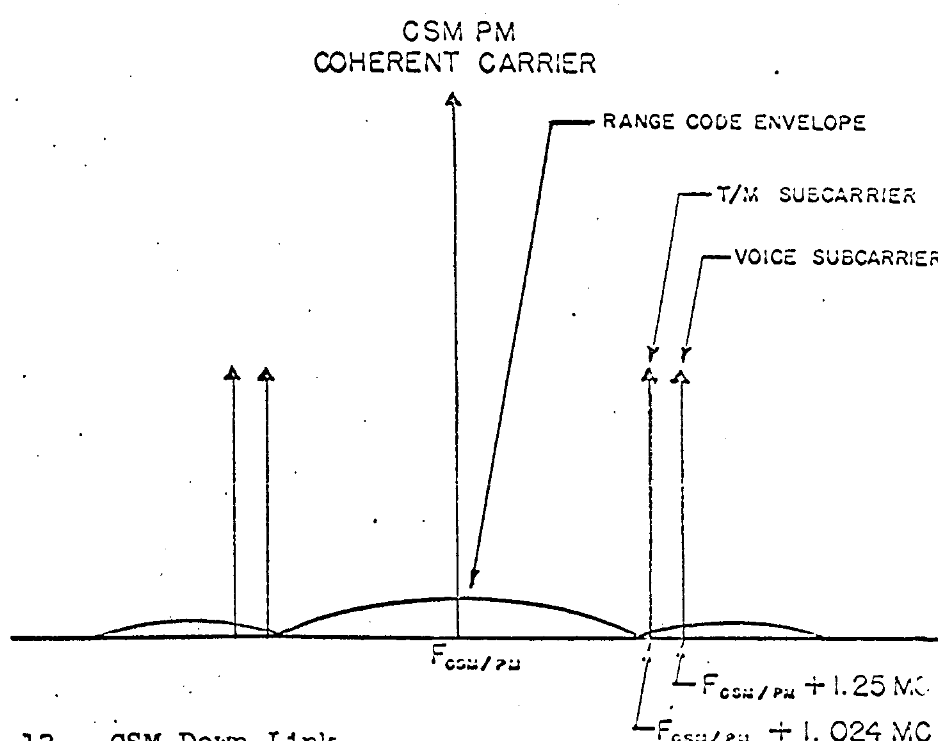


Figure 13 - CSM Down Link

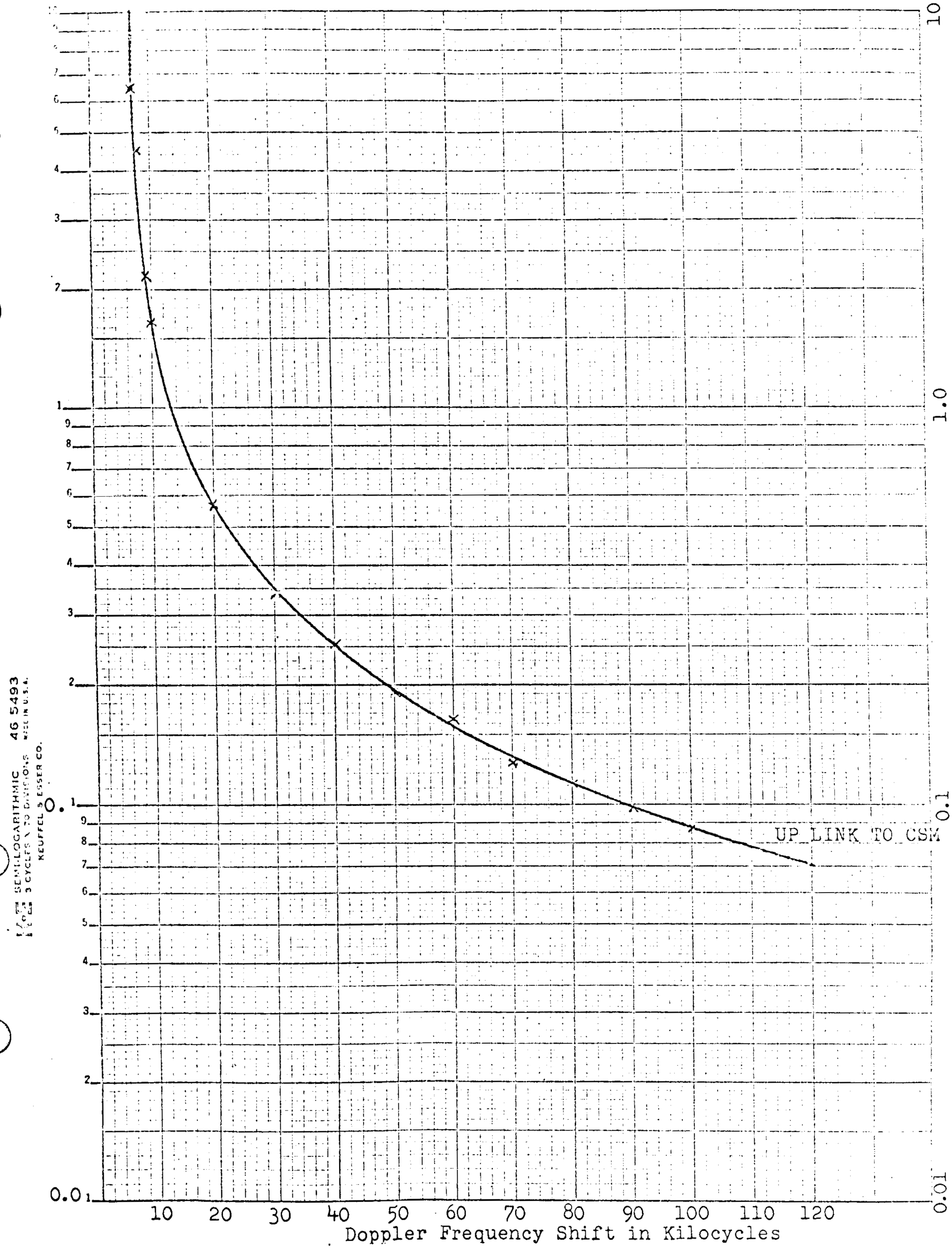
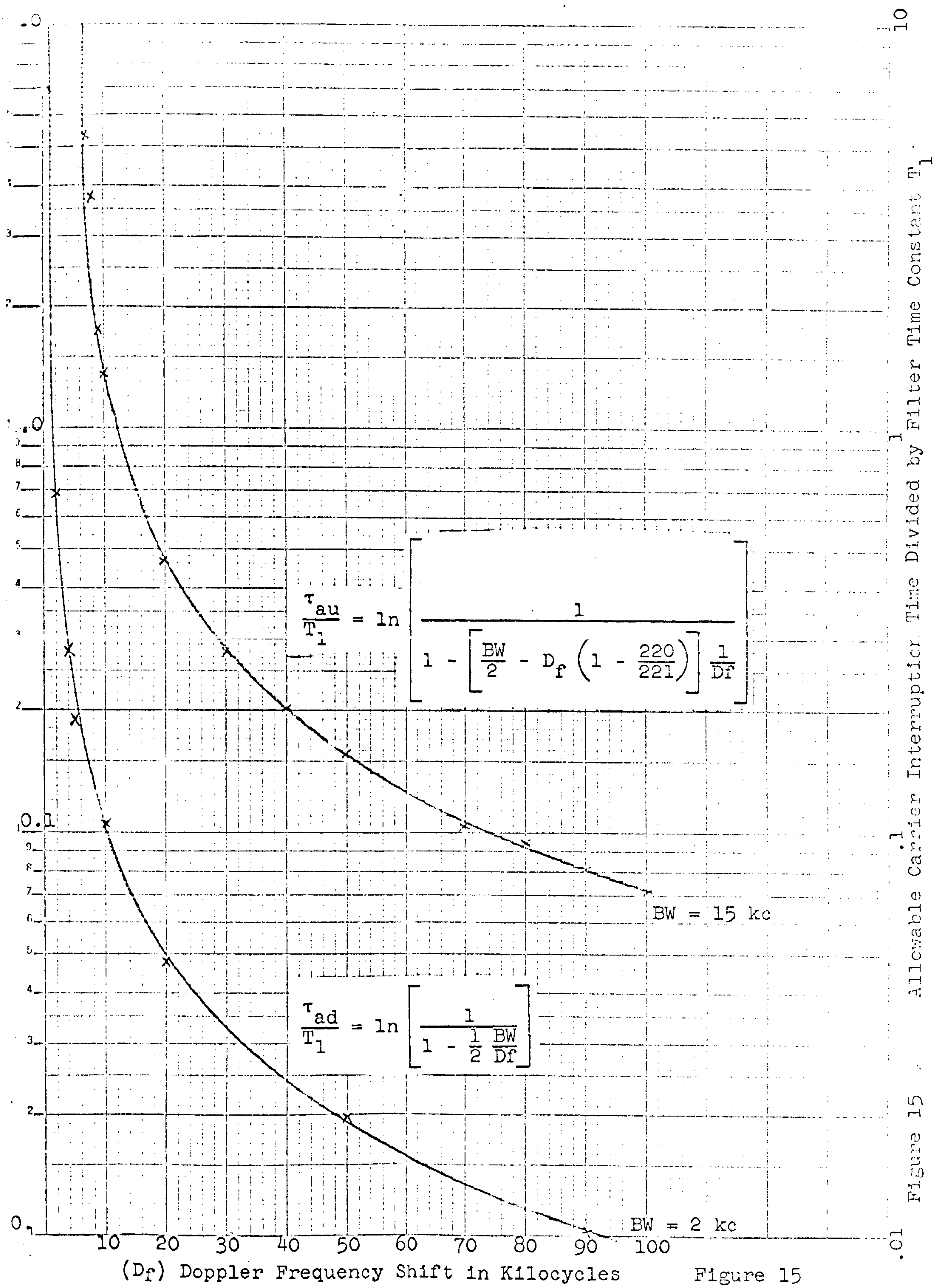


FIGURE 14 - Allowable Carrier Interruption Time in Seconds



$\frac{\tau_{au}}{T_1} = \ln \left[\frac{1}{1 - \left[\frac{BW}{2} - D_f \left(1 - \frac{220}{221} \right) \right] \frac{1}{Df}} \right]$
$\frac{\tau_{ad}}{T_1} = \ln \left[\frac{1}{1 - \frac{1}{2} \frac{BW}{Df}} \right]$
BW = 15 kc
BW = 2 kc
10
20
30
40
50
60
70
80
90
100
(D_f) Doppler Frequency Shift in Kilocycles
10
1
.1
.01
1.0
0.1
Allowable Carrier Interruption Time Divided by Filter Time Constant T_1
Figure 15

Figure 15

$7\frac{11}{16}$

$10\frac{5}{8}$

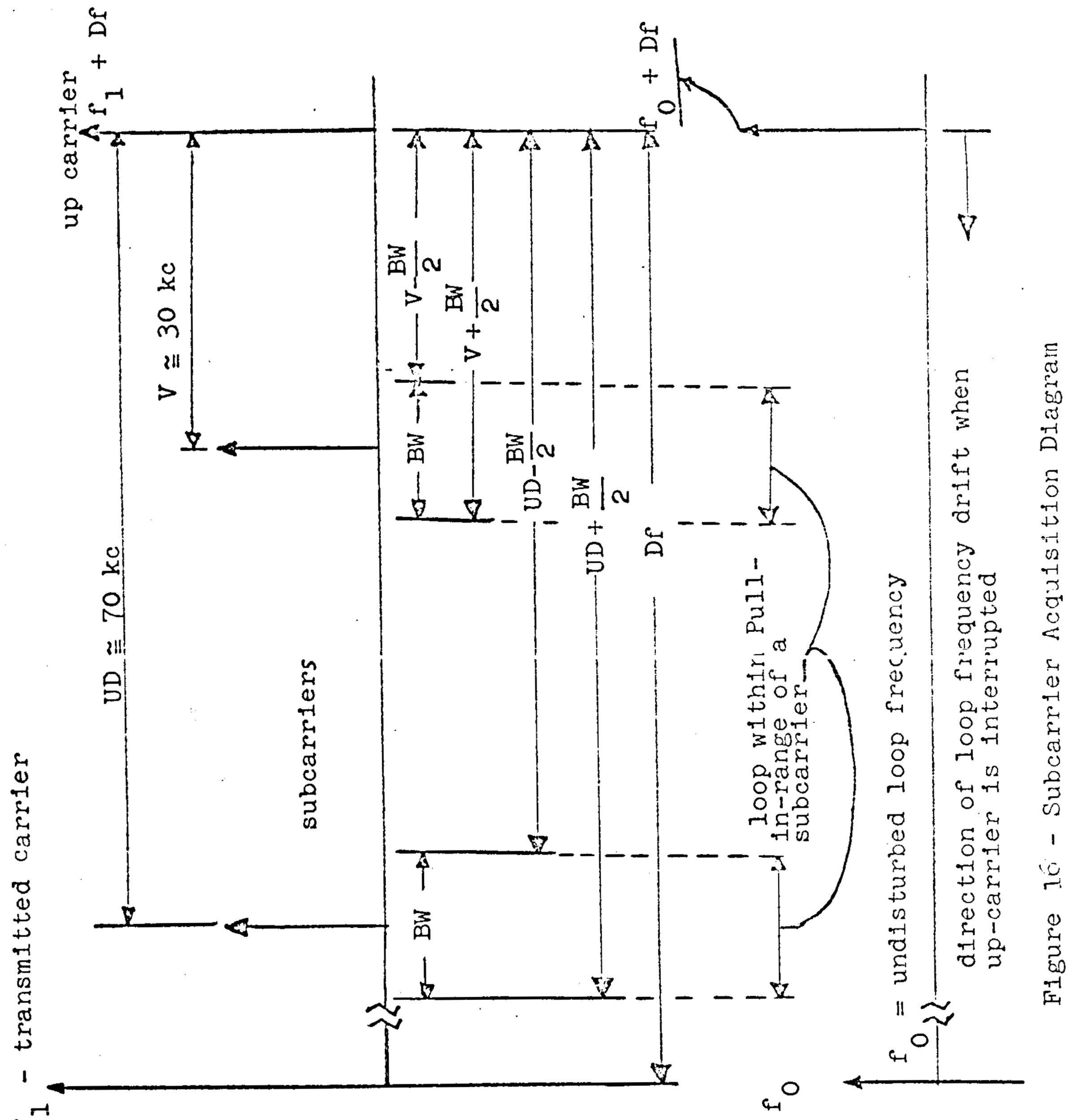


Figure 18 - Subcarrier Acquisition Diagram

ISSUE

ISSUE	ENGR	TITLE	BELL TELEPHONE LABORATORIES INCORPORATED
	DRAWN	Figure 18 Subcarrier Acquisition Diagram	SHEET
			NO. OF SHEETS PER SET

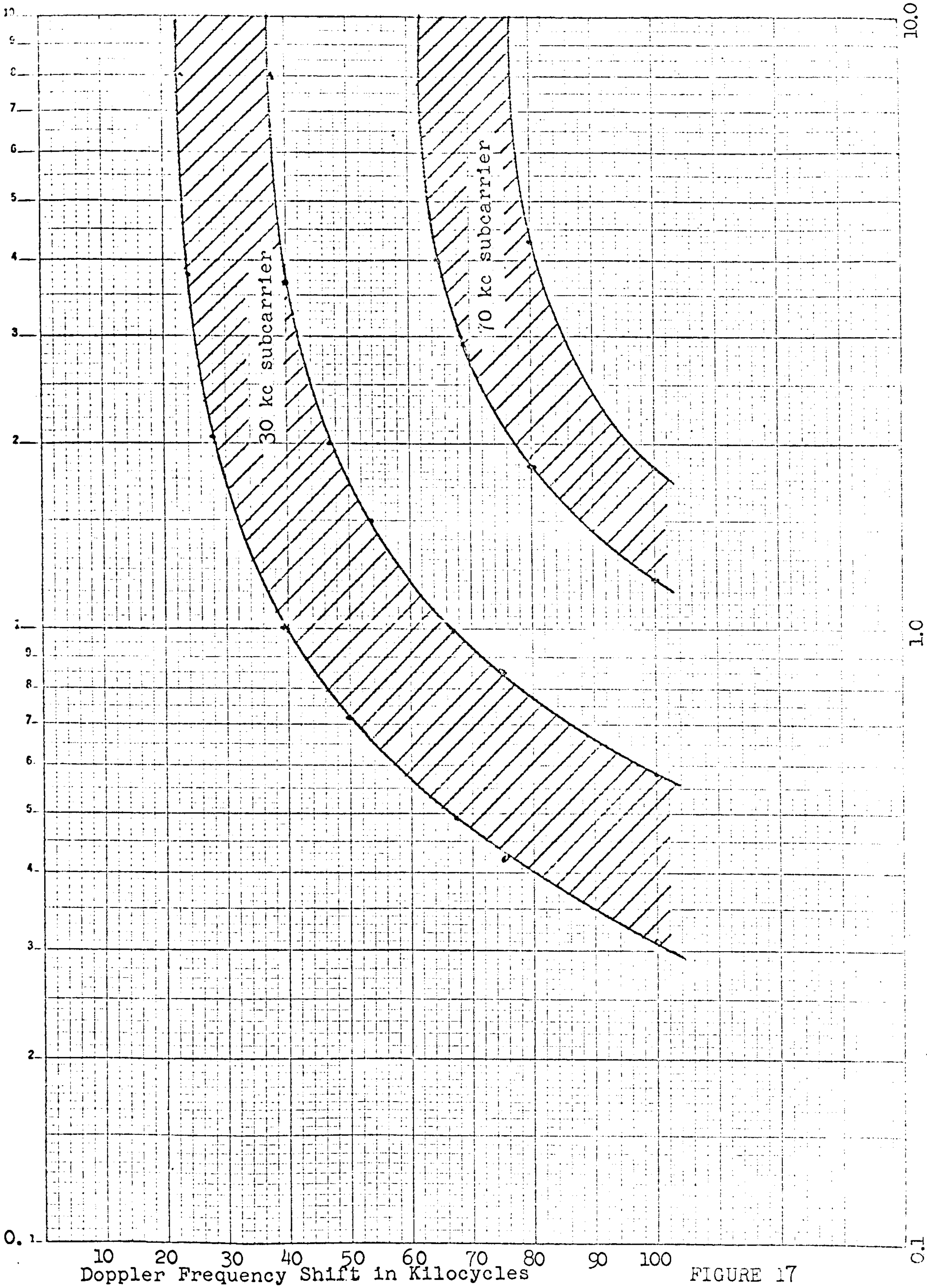


FIGURE 17

Figure 17 - Up-carrier Interruption Time in Seconds to Allow Subcarrier Acquisitions

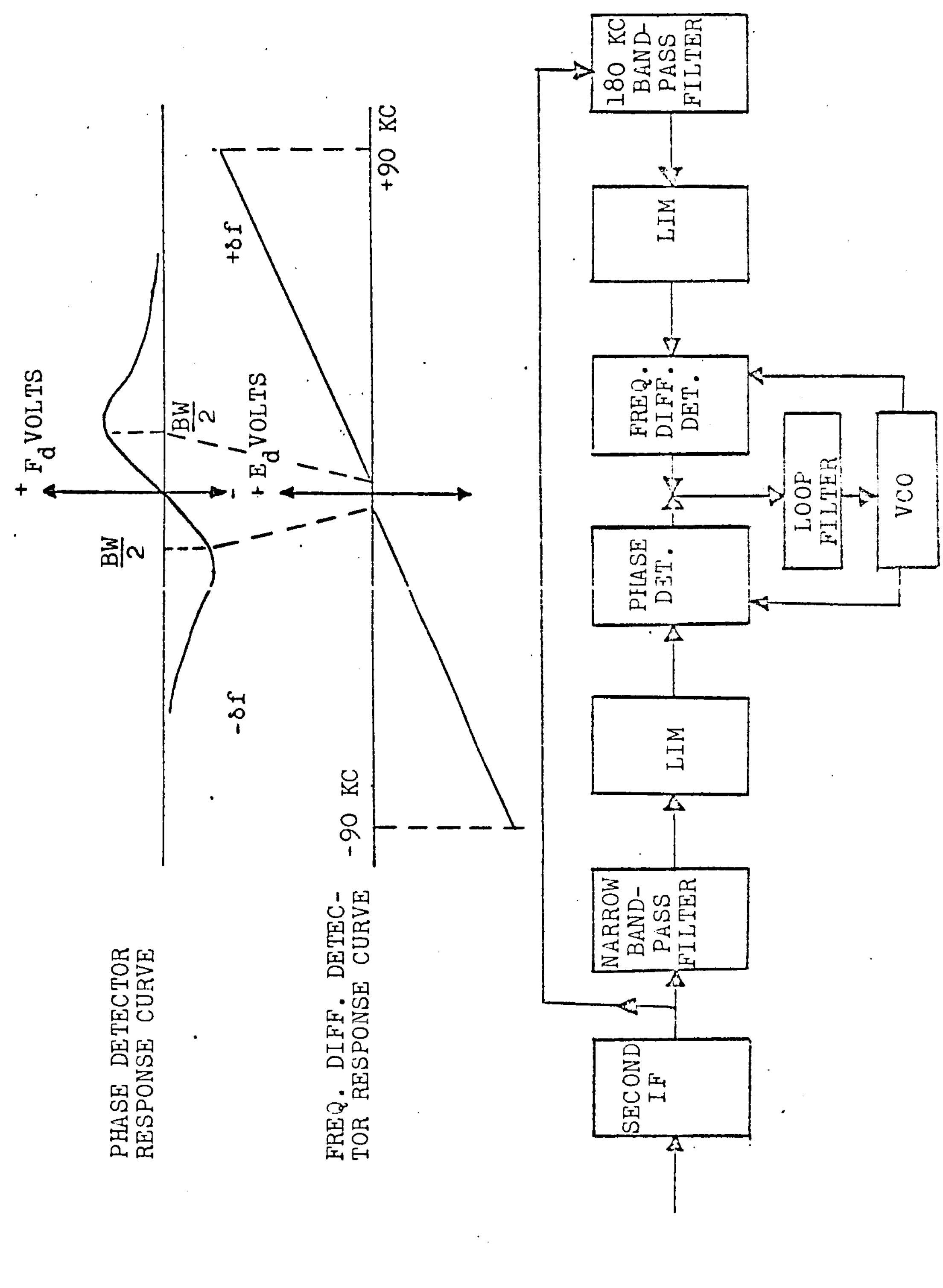


FIGURE 18 MODIFIED PHASE-LOCKED LOOP

ISSUE	ENGR	TITLE	BELL TELEPHONE LABORATORIES INCORPORATED
	DRAWN	FIGURE 18 MODIFIED PHASE-LOCKED LOOP	SHEET / NO. OF SHEETS PER SET